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EMERGING ISSUES IN SCIENCE AND TECHNOLOGY, 1981

A Compendium of Working Papers for the National Science Foundation

National Science Foundation

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Preface

In enacting the National Science and Technology Policy, Organization and Priorities Act of 1976 (Public Law 94-282), the Congress specified, in a declaration of principle, that the development and implementation of strategies for determining and achieving the appropriate scope, level, and direction of U.S. scientific and technological efforts should involve a wide range of participants from both the public and the private sectors. In particular, the act directed that a multiplicity of views be gathered in the preparation of both the *Five-Year Outlook* on science and technology and the *Annual Science and Technology Report to the Congress.*

In keeping with that commitment, and as one means of fulfilling the National Science Foundation's responsibility to provide primary assistance to the President's Science Adviser in the preparation of the *Annual Science and Technology Report to the Congress, 1981*, NSF convened a series of panels of experts from industry, government, and academia during the fall of 1981. Those panels explored the policy implications of a number of current and emerging issues in science and technology that were selected by the staff of the Foundation in consultation with advisers, in and outside of government. All issues are related to the generic theme of economic recovery, a theme at the core of the Administration's national science and technology policy.

The panels' deliberations are summarized in the eight working papers in this compendium. As anticipated, they were exceedingly useful to the staff of the NSF Office of Special Projects in assisting the Office of Science and Technology Policy with the preparation of the Administration's *Annual Science and Technology Report to the Congress, 1981*. Since the papers also delineate an important set of policy issues on the national agenda, the Foundation is publishing them separately to stimulate public discussion about the roles science and technology can play in contemporary American society. Although all of the papers were reviewed for technical accuracy, the views and perspectives they express do not necessarily reflect official policy positions of the U.S. Government or the Foundation.

John B. Slaughter
Director
National Science Foundation
June 1982

Introduction

The eight working papers presented in this compendium were prepared for the National Science Foundation (NSF) as one means to assist the Office of Science and Technology Policy with the preparation of the Administration's *Annual Science and Technology Report to the Congress, 1981*. They focus on specific aspects of three central themes that are directly related to President Reagan's goal of revitalizing the Nation's economy and that the Director of NSF, in transmitting the second *Five-Year Outlook*[*] on science and technology to the Congress, emphasized as being worthy of increased public attention. The themes are:

- the shared responsibility of the public and private sectors for maintaining the strength of the U.S. science and technology base;
- the contributions of science and technology to industrial innovation, productivity, and economic growth; and
- the changing international context of U.S. science and technology.

The papers do not provide a detailed analysis of all relevant policy issues, nor do they attempt to weigh advantages and disadvantages of possible policy options. Rather, each is intended to identify significant national issues in science and technology that are either currently on the policy agenda or likely to emerge in the near future.

Public and Private Sector Responsibilities

The first three papers in the compendium—Space Commercialization, Genetic Engineering, and Industrial Robotics—are concerned with the challenge of determining appropriate public and private sector roles for the conduct and application of scientific and technical research and development. The Administration has made clear its dual commitment to accepting the support of basic research in science and engineering as an appropriate and important Federal responsibility and to returning responsibility for most technological development projects to the private sector. Nonetheless, a few select areas remain in which the fulfillment of national needs requires the Federal Government to maintain an active role beyond the research stage.

Space Commercialization

One of those areas is space, in which U.S. Government policy has historically aimed to achieve a wide range of scientific, commercial, political, and military objectives. The Nation's space policy is now shifting from its former focus on exploring new scientific and technical possibilities toward an emphasis on exploiting past accomplishments to ensure that the sizable national investments made during the past two decades will provide greater returns than have been realized to date. Given that new focus, finding mechanisms to involve the private sector more fully in space activities will clearly be a high priority.

There is little argument regarding the desirability of commercializing space activities when feasible, particularly in view of the virtual certainty of increasingly strong foreign competition. However, significant problems still surround the transfer of any given space technology to the private sector. One of the key questions to be resolved is: What constitutes a reasonable risk for industry to take and a fair burden for the taxpayers to assume in the development of space technologies to serve multiple purposes? Candidates for commercialization include satellite communications, remote sensing, rocket launch and shuttle services, and materials processing. The feasibility of commercialization in each case and possible options for government/industry relationships in the overall commercialization process are discussed in the paper.

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[*] *The Five-Year Outlook on Science and Technology, 1981*. Washington, D.C.: U.S. Government Printing Office, 1982. NSF 81-40.

Genetic Engineering and Industrial Robotics

Genetic engineering and industrial robotics are vastly different from space science and technology—and from each other—both from a technical point of view and in the types of contributions they can potentially make to U.S. industry. However, both are examples of fields in which the Federal Government, universities, and private industry, working separately and in concert, are close to fulfilling their appropriate functions in research, development, and commercialization. Both fields have emerged from fundamental research in science and engineering, the majority of which was conducted at university laboratories and supported by public funds. Both are being actively developed and commercialized by industry (often in cooperation with universities) almost exclusively with private funds.

Genetic Engineering. The speed with which private industry has begun to use the revolutionary research results in genetics to commercialize new products and processes is impressive. A few companies began to explore the commercial implications of recombinant DNA techniques as early as 1975, only 2 years after the techniques were developed in university laboratories. Today, there are approximately 100 small firms and numerous divisions of established companies applying the techniques in an attempt to develop commercial products. The few products developed so far have been otherwise unavailable or available only in limited quantities at high cost. There are an enormous number of potential applications of recombinant DNA techniques and other recent results of microbiology research for the pharmaceutical industry, for the production of industrial chemicals, and for agriculture.

Given this contextual background, the paper on genetic engineering then highlights the current status of the technological and commercial exploitation of recent research results and also explores some of the complex policy issues—relative public and private sector roles, for example—that are emerging. Implications of increased university involvement in commercializable research, legal problems associated with patenting new life forms, and hazards, including the public's perceptions of the hazards, inherent in research on basic genetics are considered.

Robotics Technology. Robotics technology and its potential applications in industry are receiving considerable attention, primarily due to increasing public and private concerns with U.S. industrial productivity. Approximately 2,000 robots were produced in the United States in 1980, and that figure is expected to increase to 40,000 per year by the end of the decade. By 1990, the robotics market in the United States is predicted to be betweeen $2 and $3 billion annually, or about 10 percent of the anticipated industrial investment in automation equipment.

The introduction of robots into industrial production is expected to result in increased productivity, enhanced product quality, improvements in the quality of jobs, and more effective corporate responses to changing markets. In addition, it is anticipated that robots will have important uses in national defense. Because of their flexibility compared to currently operating automated equipment, robots can facilitate small-batch processing. They should therefore have a positive effect both on the competitive positions of small companies and on the national defense effort, where military procurement needs are often for items that must be processed in small batches.

Thus, the paper on industrial robotics is another case study on the shared public and private responsibilities in a potentially high-payoff, high-productivity technology. It reviews the present and anticipated future technical capabilities of industrial robots, highlights the economic aspects of and incentives for the adoption of robotics in industry, and considers the critical problem of worker displacement.

Contributions of Science and Technology to Industrial Innovation, Productivity, and Economic Growth

Genetic engineering and robotics are examples of areas in which the United States has led the way both in conducting the requisite basic research and in applying the research results to new commercial technologies. However, the dominant position of the United States in the commercialization of those and other promising technologies is in danger of eroding. The situation suggests an urgent need to make more effective use of U.S. scientific and technological resources to enhance economic growth and international competitiveness. Four papers in the compendium explore broad generic issues associated with using science and technology to increase industrial productivity: Industrial Research, Development, and Innovation; Contributions of Social Science to Innovation and Productivity; Obsolescence of Scientific Instrumentation in Research Universities; and Adequacy of U.S. Engineering Education.

Industrial Research, Development, and Innovation

The paper on industrial research, development, and innovation examines recent trends, policies, and developments that tend to encourage or discourage those activities in the private sector and discusses their implications for Federal policy. Recent initiatives in Federal tax structure, regulations, patent and antitrust guidelines, and technology transfer have been designed, in part, as incentives to stimulate industrial investments in research and development and to decrease existing barriers to innovation. Industry itself has also initiated a variety of cooperative R&D mechanisms and has taken additional steps to respond to the technological challenge imposed by foreign competition and by other market factors. Given the extensive analyses conducted, the present challenges to policymakers may be to achieve consistency and stability in policymaking and to consider aiming proposed or existing initiatives at particular industrial sectors. Clearly, such an emphasis would require greater knowledge of and attention to sectoral, regional, international, and institutional implications.

Social Science Contributions to Innovation and Productivity

Studies of social and organizational influences in industry are some of the least understood but more useful sources of information for enhancing industrial productivity and innovation. A major science and technology policy issue for the next decade, in both the public and private sectors, is to maximize the use, where appropriate, of the conceptual frameworks, findings, and methods of social science in industrial and public policymaking. The paper on the contributions of social science to innovation and productivity explores the connections between social sciences issues and the Administration's goal of economic and technological revitalization. It focuses on three types of past and current contributions of social science research to innovation and productivity: social science as a source of decision and management tools; social science as a source of social technologies; and social science as a source of general and specific knowledge on the innovation process. Major issues concerning the future structure, focus, and nature of social science research are also explored.

Instrumentation Obsolescence and the Adequacy of Engineering Education

The long-term innovative capacity of the Nation's industries depends on the continued availability of new scientific concepts, data, and technologies, and on the quantity and quality of scientifically and technically trained personnel.

Increasingly, many of the Nation's scientists and engineers who work in university laboratories cannot get access to the advanced instrumentation that in large measure determines their ability to produce groundbreaking results. The costs of developing, purchasing, and maintaining the instruments required for even the more routine types of investigations have escalated at more than the rate of inflation. Moreover, such equipment-intensive fields as physics, chemistry, the life sciences, and engineering have experienced a decade in which instrumentation has become increasingly sophisticated and expensive. During the same period, funds available for research instrumentation have declined considerably.

Since over half the basic research conducted in the United States is carried out in university laboratories, a decline in the research potential of the universities is likely to impose a barrier to the overall rate of scientific advancement. More immediately, the deterioration of university research capabilities can slow down the rate at which new types of instruments are developed for use in industrial laboratories, with potentially serious consequences for industrial innovation. The paper on the obsolescence of scientific instrumentation assesses the magnitude and possible consequences of that problem in the universities and explores a range of possible responses from industry, the Federal Government, and the universities.

In addition to facing instrumentation problems, the Nation's universities are experiencing personnel difficulties. There are serious faculty shortages in U.S. engineering schools. The shortages, exacerbated by the obsolescence of instruments for both research and instruction, have led to widespread concern among engineers in academia and industry about whether universities can retain their capacity to provide education of sufficient quality to adequate numbers of engineers at bachelor's and, particularly, Ph.D. levels. The paper on the adequacy of U.S. engineering education discusses the origins of the faculty problem and speculates about its consequences for the quality of instruction and research in the Nation's universities. Cooperative initiatives being undertaken by industry and universities to help alleviate the quality problem are also reported.

International Cooperation in Science and Technology

The final working paper in the compendium focuses on international cooperation in science and technology. The context within which the United States engages in scientific and technological cooperation has changed substantially as the United States has come to realize that it is no longer—and cannot expect to be—preeminent in all fields of science and technology. A possible framework for reviewing the basis on which to establish priorities for scientific and technological cooperation is suggested. Several categories of intergovernmental cooperation, based on the nature of the countries involved and their relationships to the United States and to one another, are explored. The growing importance of international cooperation in science and technology among private firms and universities and the important role the Federal Government can play in facilitating such cooperation are also noted. In an environment in which American preeminence in all areas of science and technology is no longer possible or, perhaps, even desirable, careful attention needs to be paid to ways in which international cooperation can complement domestic R&D efforts, conserve scarce financial resources, help U.S. industry maintain or improve its international competitive position, and contribute to U.S. political and security objectives.

While the final paper deals explicitly with international cooperation in the context of U.S. national needs and goals, each of the other papers also focuses on some aspects of maintaining the strength and effectiveness of U.S. science and technology capabilities in an era of scarce domestic resources and increasing international competition. Taken together, the papers are intended to stimulate discussion about two critical questions that lie at the heart of national science and technology policy considerations: What are the most effective investments that the Nation as a whole can make in science and technology? What is the appropriate Federal role in those investments?

Space Commercialization

Abstract

Although facilitating a more prominent role for the private sector is an important objective of U.S. space policy, that role will be constrained not only by the large and long-term capital investments involved, but also by the scientific, political, and national security objectives of the U.S. space program. Thus far, complete private sector ownership and operation has only been achieved for satellite communications. Remote sensing also has commercial promise, though complete transfer to private management is likely to be achievable with far greater difficulty. The feasibility of substantial private involvement in space conveyance services and in materials processing is also receiving considerable attention. Other commercialization prospects, such as solar power satellite systems and space mining operations, are not regarded as likely candidates for the near future. Any realistic strategy for encouraging space commercialization must recognize that Federal involvement, at least in the initial developmental stages, is a prerequisite for a viable private sector role. Conversely, early and effective private sector involvement in space technologies could help determine fruitful, exploitable research directions and also ensure the development of services and systems that meet the criteria of commercial operation.

Introduction

The commercial exploitation of space has, in recent years, become a topic of serious policy consideration for a number of reasons. Foremost among them is a belief that after more than two decades of an active space program, it is time for the sizable national investment in space to pay off to an even greater extent than it has to date. Given current constraints on the Federal budget, coupled with the Administration's active reassessment of the proper relationship of government and business, an increased focus on the role played by the private sector in facilitating the economic growth and well-being of the United States is sure to continue. Such fundamental policy considerations will have an impact on all commercialization and technology transfer decisions, including those pertaining to space.

There is little argument regarding the desirability, in principle, of commercializing space activity whenever and wherever feasible. The contribution of satellites to the development and expansion of our communications capability serves as an encouraging example of the payoffs possible from timely R&D efforts and industrial involvement in exploiting technological developments. However, a number of basic problems surround the transfer of any given space technology or activity to the private sector. The problems become especially troublesome if commercialization is understood to mean private sector ownership rather than some such hybrid arrangement as Federal ownership and private management or the creation of a publicly funded corporation. In all areas of space activity, one of the key questions is: What constitutes a reasonable risk for industry and a fair burden for taxpayers in the development of space technologies that will serve multiple purposes for the Nation?

Consideration of what space activities can be commercialized and how, and what the appropriate government/industry relationship should be, cannot be separated from other important considerations imposed by the multiple objectives of U.S. space policy. Although a prominent and responsible private sector role in space is one of the implicit objectives of that policy, the role needs to be evaluated and understood in relationship to other goals important to national well-being. The attempt to meet those various goals may at times create dilemmas and constraints for enhancing the role of the private sector.

An Overview of U.S. Space Policy

U.S. space policy has sought to achieve a wide range of objectives including national security, U.S. economic and political leadership, international cooperation, commercialization, and scientific progress. The initial premise of implementing a space program with a large civil component was that the undertaking was of great benefit to the Nation and thus was worthy of large-scale public support. That premise has been elaborated in the National Aeronautics and Space Act of 1958 and its amendments.

Entry into space has necessitated the development of new technologies to conquer and to utilize effectively the advantages and opportunities presented by the new environment. It has also required the creation of an entirely new infrastructure where none previously existed. Parallels to this situation can be found throughout U.S. history where, at crucial points, the Federal Government played a pivotal role in underwriting the Nation's development by subsidizing particular industries, especially in trade, railroad construction, and land development.

The large task of creating a space infrastructure to support technological development has been influenced primarily by military and national security objectives, although the creation of the infrastructure has fulfilled other purposes as well. The advance of communications and information technology has been important for national security reasons and for maintaining U.S. leadership in key high-technology areas. Remote sensing, like satellite communications, provided many areas of the world with otherwise inaccessible services, established the United States as world leader in the field, enhanced international cooperation, and provided information on world resources vital for planning, economic development, national security, and public benefit. Finally, the space shuttle has been developed to serve both civil and military needs. It, in particular, is perceived as playing a vital national security role.

The International Context

The crafting of a long-term investment program in space in an era of budgetary constraints will be complicated considerably in the years ahead by discussions and rulemaking on space in the international arena. Far from being esoteric and of interest to only a few nations, space issues have evoked worldwide concern and involvement well beyond the members of the "space club," those nations with active space programs.

Experience with some issues recently discussed at the World Administrative Radio Conference—for example, the Moon Treaty, direct broadcast satellites, and solar power satellites—points to a determination on the part of the world community, and particularly third world nations, to design a set of rules that would preserve and set aside opportunities for latecomers. Negotiating rules that establish a predictable and reasonable framework for the continued development of space while preserving the flexibility necessary to respond to changes and challenges in the space environment and to encourage private industry's involvement is one of the most important political and economic challenges of the next decade. The ability of the United States to respond constructively to pressures to explore and exploit the Moon, for example, or to build space manufacturing facilities to process resources originating from space will depend on a clarification of rules governing the extraction of space resources and a framework of international cooperation and even collaboration in space.

An Overview of Public and Private Sector Roles in Space Commercialization

While a fundamental belief in the benefits of a major public investment in space has served as the basis for all space development activities, the evidence for a profit, from a cost accounting perspective, resulting from the Nation's space investment is difficult to pinpoint. Many more years may be required before a reasonable assessment can be made. Only in one area, communications, can the short-term tally be shown to justify the initial investment. Although the eventual commercial benefit of space development is incalculable, it is nonetheless thought by many to hold great promise. However, any intensified private sector role in space development will have to be premised on the existence of a space program that is long range, diversified, and founded on a strong science and technology base. Appropriate Federal decisions and strategies concerning private industry's role first must focus on the commercial opportunities being created by the Nation's space program.

The range of private sector involvement and the forms some commercial ventures have taken vary a great deal. Complete private sector ownership and operation has been achieved only in satellite communications and may possibly, though with far greater difficulty, be achievable in remote sensing. Space development has, however, promoted private sector participation as contractor and supplier, as developer of secondary services (for example, value-added processing of remote sensing imagery), and as transformer of space technologies into new commercial ventures and applications.

Unfortunately, the public debate on commercialization and space frequently casts the Federal Government and private industry as antagonists. The fact is that broad-based Federal space policy has not been the antagonist; it is, rather, the basis of commercial profit from space. Once that is understood, the key issue for the future becomes not how to remove the Federal Government from the picture but how to develop or define the most positive and appropriate role government can play in the commercial development of space technology and space systems.

Candidate Activities for Commercialization

Although the initial investigations of civilian uses of active communications satellites were done by American Telephone and Telegraph Company (AT&T), the National Aeronautics and Space Administration (NASA), in the early sixties, pioneered geosynchronous communications satellites. Since then, many other types of space activity have been developed and now are viewed with varying degrees of optimism as candidates for future commercialization. For example, remote sensing has been, for the last few years, the focus of intensive scrutiny, both within and outside of the Federal Government, to determine whether transfer of any portion of its operational responsibility to the private sector is feasible and, if so, under what conditions. Such other space activities as shuttle operations or space manufacturing are recognized as somewhat more distant candidates for commercialization if the proper circumstances prevail.

Three major categories of space activities, each with varying potential for commercial exploitation, are discussed briefly below:

- space-assisted communications and information services,
- space conveyance, and
- space industrialization.

There are obvious differences in the maturity of these activities and the possibilities for their technical exploitation. Other dimensions on which the activities covered by these categories differ include the availability of ready or plausibly developable markets, the relationship of the technology to national security and other public policy concerns, the constraints that could be imposed by the international political environment, the investment of capital required, and the risk any public or private investment would entail.

Space-Assisted Communications and Information Services

The two space activities with the most immediate commercial application, satellite communications and remote sensing by satellite, are essentially land-based activities in which satellites play a crucial role in recording or relaying information from one point on the earth's surface to another. In neither case, however, has industry assumed a leadership role without aid. In both cases, the role of the Federal Government has been important, though in varying degrees, and, in the case of remote sensing, successful transfer to private ownership has yet to occur.

Satellite Communications. The communications satellites pioneered by AT&T in the late fifties and by NASA in the early sixties lent themselves to immediate and highly successful commercial exploitation. Indeed, the extraordinary growth of the domestic and international communications satellite industry has made it logical to point to its success story as a model for future space commercialization efforts. However, the relatively easy success of satellite communications may have been more an exception than a pattern. The single most important factor accounting for this success was the existence of an already well-developed market served by an established private industry. Communications is the only area, thus far, where that condition has existed with respect to applying space technology to commercial operation.

Nevertheless, even the highly positive market conditions were not sufficient in and of themselves to ensure the long-term commitment of private sector involvement and takeover without some Federal assurances. Thus, during the Eisenhower Administration, private industry was initially reluctant to assume all the initial risk of developing satellite communications without assurances that the government would provide launch services for any new technology developed and would not enter into direct competition with private sector development. Later, under the Kennedy Administration, Congress perceived it in the national interest to have the technology implemented and decided to enter into the communications satellite business by passing the law creating a quasi-private, quasi-public communications satellite corporation, COMSAT.

More recently, advances in communications and information technology and continued development of receptive markets have resulted in a period of rapid growth, diversification of services and service providers, and high profits in the communications and information industries. Both established carriers and newcomers have, in an environment of deregulation and increased competition, moved to take advantage of and promote the opportunities made possible by technical advances in those industries. Currently, the principal challenges confronted by the industry are the limitations on the radio frequency spectrum, the availability of space in the geostationary orbit, and the restrictions (for example, *a priori* planning for frequency and orbit use) that could be imposed by international bodies regulating both resources.

Clearly, the existence of a strong private sector communications industry with large, well-established markets, by which the technology could be readily exploited, was of fundamental importance to the success of commercialization efforts. The technological advances made possible by NASA research and development served, in effect, to extend at a propitious time the reach and scope of a service already being supplied by other means. More recent strategies for exploiting new communications technologies have not required a public demonstration model and initial investment of public funds. However, strategies used by private firms to provide innovative telecommunications and information services may be indicative of the types of institutional arrangements needed if other space activities are to be successfully commercialized. Specifically, the creation of Satellite Business Systems, combining the resources of three large companies (IBM, COMSAT, and Aetna), has raised the question of what resources, both institutional and financial, are required to reduce anticipated market risks to acceptable levels. That, in turn, may have some implications for antitrust considerations and the direction that targeted deregulation may have to take.

Remote Sensing. After satellite communications, remote sensing from space appears to be the most promising of the space activities for near-term commercialization, although current budget battles may render such commercialization moot. The technology used to sense the earth from space to estimate crops, map terrain, and make inventories of resources has been available on a demonstration, quasi-operational basis for approximately a decade. The utility of the imagery from the resource-sensing satellites of the Landsat series is widely acknowledged, although its ultimate benefits cannot be estimated accurately in dollar amounts. Over 100 nations have purchased Landsat data from the Earth Resources Observation Systems (EROS) data center operated by the Department of the Interior, and 13 have bought their own earth stations to be able to receive Landsat data directly from the satellite. Domestically, several Federal Government agencies rely routinely on Landsat data to conduct a portion of their business, and State and local governments have similarly increased their reliance on satellite imagery. Through contract arrangements with the federally operated program, first with NASA and now with the National Oceanic and Atmospheric Administration (NOAA), private activity to date has focused primarily on build ing satellites for the Federal Government and on providing value-added services to other, mostly private clients by enhancing Landsat imagery.

In the wake of increasing administration and congressional interest in assessing the feasibility of transferring operational responsibility for remote sensing to the private sector, specific mechanisms need to be explored both by the Federal Government and by private firms. Past efforts to devise plausible strategies for that transfer have encountered some difficulties. Remote sensing, especially in its quasi-operational phase, has never been a self-sustaining enterprise, and returns on the purchase of data have not come close to matching the costs of operation.

Unlike satellite communications technology, remote sensing has not emerged within the context of an established and growing market served by a well-developed and thriving industry. In fact, the technical and market risks associated with satellite communications pale by comparison to the problems confronted by remote sensing. The need to develop markets while simultaneously defining the parameters of an internationally competitive and commercially sustainable system is quite a challenge. The uncertainties are reinforced by other, international factors. Among them is competition from the French remote sensing satellite, SPOT, now slated for implementation in 1984-1985. That system's development and operations will be supported by the French government, and its performance may make some of the capabilities of the U.S. system obsolete. The international rulemaking process might impose restrictions inimical to commercial expansion of the collection and dissemination of data, causing an additional problem. Even if the U.S. Government makes no attempt to recover development costs (and none is likely), it is difficult to conceive of a single industry being willing or able to shoulder all the investment risks required for operational transfer.

Within this context, efforts to maximize private sector involvement may require both compromises and imaginative institutional solutions. The primary issue may be not whether a private company can successfully operate the system but, rather, what entry conditions must be considered to reduce the overall risk of initial investment to acceptable proportions without, at the other extreme, presenting an outright handout. If the Federal Government decides that continued U.S. leadership in remote sensing is a worthwhile national goal, new institutional arrangements to achieve that goal will have to be sought. It is currently thought that continued, but decreasing, public support during the transition period will be the case. One possible solution would be for the Federal Government to launch Landsat-D if private industry agreed to take over its operational responsibility.

Space Conveyance

Technology has now made two types of conveyance to space possible: the expendable rocket and the reusable space shuttle. The intention of U.S. space policy has been that shuttle services would, once developed, be relied upon for the transfer of objects and human beings to orbit. However, the future is likely to allow purchasers of transportation to space to choose from a variety of options, including the shuttle, the French rocket Ariane, U.S. rockets, and even launch by a domestic or foreign company, for example, OTRAG, a German-based, private rocket development company, or its American counterpart, Space Services, Inc.

Rocket Launch Service. Future U.S. deemphasis of traditional rocket launch systems as a consequence of encouraging shuttle use has not dampened interest, both domestic and international, in the commercial possibilities of rocket launch services. Based on the continued demand for space conveyance (especially for commercial communications payloads), the French government decided that a launch capability priced competitively with shuttle fees could become a successful commercial venture. That belief in the continued competitiveness of expendable rocket launches may have been well placed. Delays in NASA's shuttle program have generated concern among potential launch customers so that some customers, to ensure delivery of their satellites into orbit at required times, have made inquiries of the French. The attractiveness of the traditional launch method has also been enhanced by the escalating costs of the shuttle program and the expectation that future operational costs could sharply outstrip initial expectations.

U.S. private enterprise is also taking on the calculated risk that traditional launches will remain a profitable alternative for some purposes. Thus, Space Services, Inc., a private company based in Texas, tested its first rocket in mid-1981. Although the first test proved unsuccessful, it was, nonetheless, the opening shot of a venture intended to provide cheap, reliable launches as an alternative to government-sponsored systems. The endeavor of Space Services, Inc., is particularly noteworthy in that it is a rare example of a private company deciding to proceed in a space activity without initial government assistance.

How successful private efforts to develop a space launch capability will be is not clear. Even though the launch technology is well established and accessible, adequate standards of reliability and control may require more of an investment and higher fees for service than initially imagined. Nevertheless, a cautious prediction might be made that rocket launches under private commercial sponsorship will eventually become a fixed part of the menu of space services available to those who require them, provided no undue obstacles are presented by domestic or international law. One potential domestic obstacle is whether the Federal regulatory structure is applicable to private launches from U.S. territory.

Space Shuttle. The new U.S. Space Transportation System (STS), based on the shuttle, opens up the possibility of a new era in space. The shuttle is a reusable vehicle that can deliver and retrieve payloads as well as serve as a temporary in-orbit base for operations, experimentation, and repairs. More than an alternative launch vehicle, it is capable of transporting larger satellites into orbit than conventional rockets can, and it is highly maneuverable.

Although probably not realistic in the near future, private sector operation of the shuttle has always been an option under consideration. Proponents point out that once STS is established it ceases to be the object of research and development, except in the case of refinements to the technology. The appropriateness of NASA's continuing role as the system's operator may, therefore, be an issue if a strict interpretation of NASA's charter as one that confines the agency to an R&D role is taken.

As a practical matter, however, a reasonable strategy for the private takeover of STS operations or even a portion of them is difficult to devise. First, STS was developed for joint civilian and military use. Not only is the shuttle expected to carry civilian and military payloads, but it has been proposed that the two launch sites and at least a portion of mission control will be used in common. Second, the enormous cost of the entire system makes duplication for commercial purposes unlikely in the foreseeable future. The cost of the system was a primary consideration for the dual use and, therefore, by extension, argues against the possibility or advisability of disaggregating the system into civil and military components.

Thus, devising plausible strategies for commercializing (i.e., promoting private ownership or operation of STS) becomes difficult. The multipurpose approach, strongly focused on serving national security requirements, frustrates possible notions of reserving portions of the system for private sector development. Assuming a willingness on the part of a single company or, more realistically, a consortium, to invest the $1 billion needed to purchase shuttle technology, questions would still remain about how a private orbiter could be integrated into the existing operational scheme. A time- or cost-sharing scheme might be one solution. Equally puzzling is the question of how a privately owned vehicle would fit as a user of an integrated Federal facility.

If the nature of STS precludes even limited private ownership, a long-term alternative strategy might include a gradually expanding private role achieved by leasing STS to a private operator through a GoCo (government-owned, contractor-operated) arrangement. The GoCo concept is well established as an acceptable arrangement by which private contractors operate key facilities for the Department of Defense. Assuming the establishment of a management and operations scheme adequately responsive to national security requirements and assuming, as well, an increased economic viability for STS, this kind of limited commercialization of the shuttle might be possible.

Space Industrialization

The cluster of activities described under the rubric of space industrialization is a far more distant, long-term component of the space development program. If those activities were to reach fruition, they could eventually enhance the commercial relevance of STS and provide a rich potential for private industry's involvement. As in the preceding cases, however, realizing that potential will no doubt hinge on maintaining a broad-based, federally funded space program that establishes a plausible investment and risk climate for the private sector.

Materials Processing in Space. Materials processing in space offers the possibility of using the low-gravity and high-vacuum environment of space to produce certain classes of alloys, pharmaceuticals, glasses, semiconductors, and superconductors. Initial space experiments with materials processing took place in rockets that simulated the environment of space. Future experiments are slated to use the shuttle to deliver payloads into orbit and retrieve them.

With the inception of NASA's Materials Processing in Space (MPS) program, there was a clear and immediate perception of the need for private involvement from the outset to ensure the most favorable circumstances possible for systematic commercialization. The programmatic approach of MPS could be construed as a deliberate mechanism to correct the long, drawn out experience of attempts to commercialize remote sensing. The two central elements of the MPS program were the establishment of a solid processing research base and early industrial involvement. In addition, the establishment of cooperative international research activities and the development of nongovernment facilities of national stature for independently funded space research reinforced the vitality of the program.

NASA's creative thinking yielded some early positive signs of industrial interest. For example, McDonnell Douglas Company and Johnson & Johnson entered into a joint agreement with the space agency for a materials processing experiment to be flown on the shuttle. The joint venture commits the two parties to provide specific materials and services (shuttle transportation and integration by NASA, the experiment by McDonnell Douglas and Johnson & Johnson), but no money will change hands. This agreement mechanism could be a great facilitator in the future of joint public and private projects.

Sustained commercial development of this kind will require the continuation of the NASA MPS program, continued availability of such creative institutional arrangements as the joint venture described above, and reliability of STS for delivery and retrieval of experiments and, eventually, marketable payloads on a reasonably predictable production schedule. Further expansion of MPS into a permanent, stable, fully developed industrial venture must, however, be viewed as belonging to a more distant future when and if the unfolding of a comprehensive space industrialization capability becomes possible.

Solar Power Satellite. Many of the general observations made about materials processing also apply to the possible development and commercial operation of a solar power satellite (SPS) system. Such a system entails the development of some means to capture solar energy in space, transmit it to earth, and convert it into electricity. The most likely system now proposed would place solar panels in space to beam solar energy to earth through microwave transmission. SPS differs from MPS in several crucial respects that, taken together, indicate that the development of solar power from space may not be feasible in the near future. SPS would require a prior substantial development of the space infrastructure—a manufacturing capability and large, flexible, platform construction. In other words, the viability of SPS is dependent upon a broadly developed space capability. The impetus for the establishment of such a capability is directly related to R&D costs and how those costs relate to the availability of alternative energy sources. Development of the SPS system will also be affected by international rulemaking. Decisions about microwave transmission of solar energy to earth were set aside in an atmosphere of some controversy at the 1980 World Administrative Radio Conference. It is clear that despite steadily rising costs of terrestrial energy sources, the space-based solution is still a long way from becoming a cost-effective, environmentally acceptable reality.

Space Mining. Although clearly a long-term future development, space mining has already been the subject of vigorous public debate. Terrestrial resources no doubt will remain adequate for the foreseeable future. Yet the eventual exhaustion of particular terrestrial minerals may one day make mining the Moon and other planetary bodies more attractive, especially if building in space becomes a reality.

Like the previous issues, space mining will require certain prior conditions, for example, the continued development of a broad space capability, an increased need on Earth for space-derived materials, a feasible risk situation for private industry, and an acceptable international framework.

Questions concerning the international framework have assumed an early and urgent significance because of the Moon Treaty. Formally titled "Agreement Governing the Activities of States on the Moon and Other Celestial Bodies," the treaty was drafted in the U.N. Outer Space Committee and was submitted in 1981 to individual nations for ratification. Lack of clarity in key provisions governing the exploitation of lunar resources and the consequent controversy raised questions about whether the treaty could provide an environment appropriate for active private sector pursuit of space mining.

Issues and Choices

The objective of maintaining U.S. world leadership for national security and economic purposes, the many objectives of the U.S. civil space program since its conception, and the broad requirements of maintaining a workable research and technology base for a sustained space capability form a complex and sometimes conflicting context within which to pursue commercialization.

Nonetheless, several factors point to the possibility of a more active future involvement by the private sector in space activities. First, left to itself, technical development and refinement can be extended indefinitely, and those involved can demonstrate a reluctance to "freeze" the state of the art for purposes of general transfer and use. From this perspective, it is argued, focusing on the "readiness" of technology developed under Federal auspices can be misleading and distract from the central issues, which are the receptivity of the market for the technology or technical system and the technology's commercial feasibility.

Second, a primary purpose of space-related R&D is to enhance the position of the United States in international trade and to sustain competitiveness and, wherever possible, leadership in technical areas. Early industrial involvement or even primary responsibility for the activity is essential to the achievement of that purpose and the successful accomplishment of commercial adaptation. Where private sector involvement is most appropriate, technologies can be developed with an explicit eye toward existing and potential markets, and system requirements can be defined to meet common denominator standards of reliability and service delivery instead of being geared to exciting but perhaps commercially inappropriate technical advances. Early and effective private sector responsibility could thus be perceived as playing a crucial role in selecting, from a range of possibilities, those activities that are clearly marketable profitably, thereby obviating the extended and costly pursuit of those technological alternatives where the ultimate economic payoff is questionable.

Finally, the nature of the U.S. political economy plays an important role in defining the most appropriate modes for adapting technological innovations and improvements stemming from Federal research and development activities to new commercial purposes. The traditional role of the private sector as an independent, self-motivating, creative producer of goods and services provides scant legitimacy to the Federal Government in the role of market developer, sales agent, and, at times, even R&D performer. In effect, the Federal Government is relatively less effective as a vendor than a private company in commercializing and exploiting an ongoing, profitable endeavor.

However, any realistic strategy for encouraging commercialization must recognize that Federal involvement in the initial phases of developing a space program is not antithetical to a private sector role but, rather, is often a prerequisite for such a role. The experience of the last 20 years has demonstrated the reluctance of industry to undertake risk of assuming ownership and operation of innovative space systems or initial responsibility for the required basic research.

Thus, encouragement of greater industrial involvement in space and in other high-risk technology areas may be achieved by a coherent cluster of policies that enhances the attraction of unusually long-term investments in select areas where development is judged to be in the national interest. The risks may be further attenuated by the pursuit of innovative institutional arrangements—for example, joint ventures, public/private corporations, consortia for research, development, and even operation of space technology, and the like. That kind of policy framework could relieve the Federal Government of at least a portion of the financial burden it now assumes in underwriting the initial development of space activities.

However, it would be unrealistic to expect industry either to assume primary responsibility for civil space development or even to take, unaided, the first steps in assuming ownership of major space systems. From both perspectives, the Federal role will be of critical importance. The key elements of that role will continue to be, as they were in the past, responsibility for long-term R&D and the delineation of a policy framework that encourages private participation and responsibility in partnership with the Federal Government. Strategies used in the past clearly will require careful reassessment with an eye toward limiting the extent and duration of Federal involvement in areas that could benefit from an earlier and more extensive private sector role. Ultimately, effective private involvement in a variety of space technologies could help rationalize the costs of R&D deemed appropriate for public support; help determine fruitful, exploitable directions for space research; ensure an expeditious development of relevant markets; ensure the development of services and systems designed to meet criteria of commercial operation; and, perhaps, contribute in a variety of ways to reducing the total amount of public support now needed for space activities.

Genetic Engineering

Abstract

Revolutionary advances in the basic knowledge and understanding of the genetic code that programs the development of every living organism have enabled molecular biologists to develop a new set of techniques, known as recombinant DNA technology or genetic engineering. The new era in genetics holds vast promise for the direct treatment of genetic diseases, the production of revolutionary drugs, the synthesis of industrial chemicals, the development of new agricultural species, the recovery of mineral resources, and many other areas. A sizable amount of funds has been invested in many new companies formed to conduct research and exploit the field. There is also increasing activity in older large companies. University researchers are active participants in the ventures, and the exciting commercial potential of research has intertwined university and industrial science to an extent that some see as a threat to traditional and fruitful academic research. Educational resources are likely to be severely challenged by the need for large numbers of professionals in many allied fields. Although a recent Supreme Court decision has established the patentability of genetic engineering results, complex proprietary problems remain. The National Institutes of Health (NIH) Guidelines, stimulated by the concerns of scientists and the public at large about the unwitting release of disease-causing organisms, have come under recent review. A decision was made by the NIH Recombinant DNA Advisory Committee (RAC) to keep the mandatory rules, but relax their provisions. Evaluations of other hazards still require substantial attention. Federally supported research created the field, and such funding will continue to be warranted for the basic science complementing the now much larger commercial investment.

Introduction

In 1953 Watson and Crick provided the understanding necessary to "crack the genetic code." In doing so, they were able to explain the basic structure of deoxyribonucleic acid, or DNA, the molecule in all living things that contains the totality of genetic information and programs their development. DNA was discovered to be a long, twisted, ladder-shaped molecule (double helix), whose rungs always consist of pairs of the same four subunits. Differences between the genetic program of one species and that of another are due to the varying arrangements of those basic subunits.

The unit that determines a specific characteristic of an organism is called a gene and is frequently made up of a number of adjacent rungs on the DNA ladder. One of the gene's functions is to program repeatedly the creation of a specific protein in a cell (for example, a hormone), which in turn has its own specific function in the organism.

With that basic knowledge and understanding, a new era opened. Molecular biologists began developing a new set of techniques, known as genetic engineering or recombinant DNA technologies, whereby specific genes can be removed from one species and spliced into the DNA of another. Once such a genetic transfer is successful, the recombined DNA can indefinitely replicate as the host reproduces. Recombinant DNA (r-DNA), gene splicing, or genetic manipulation techniques allow the transfer of genetic information not only within species, but between species belonging to widely different kingdoms of life. Thus, genetic engineering provides virtually unlimited prospects for the development of new strains of organisms that can be modified to serve human needs either by the acquisition of useful characteristics or by the production of new products. The insertion of a single gene into a bacterium, causing it to produce a targeted product, will be a common example of recombinant DNA technology.

Recombinant DNA techniques, which have been used in the laboratory to produce human insulin, growth hormone, and interferon, are now being introduced into the marketplace. Indeed, the prospects for applying the techniques to medicine, agriculture, energy, and other fields seem virtually limitless, and an aggressive new industry has emerged to put the new technology to use. Potential applications include production of new vaccines, control of genetic disorders, improvement of agricultural yields, and production of new energy sources. The largest markets are likely to develop in the chemical and agricultural industries.

The sudden emergence of the innovative technology, with its potential broad applications and social significance, is expected to generate, along with opportunities, attendant problems and anxieties with which society must grapple. A great deal of time and effort has been devoted to anticipating and assessing the risks inherent in the technology and the potential biohazard that could accompany its widespread application. Clearly, the risks will need continuing reevaluation. This paper focuses on the benefits and advances that can be expected from the commercialization of recombinant DNA technology with a view to identifying what initiatives, if any, the government may need to take in fostering and, if necessary, regulating those activities to maximize the benefits and minimize the risks to society.

Current and Likely Applications

It is impossible to assess with any confidence, or in any detail, the future commercial significance of genetically engineered products. Both the substances and the production techniques yet to be developed may be quite different from the ones now being used. A striking example, however, gives some understanding of the excitement that has been stimulated. The hormone interferon, known to be effective as an antiviral agent and under study as a potential anticancer agent, is now being made by conventional extraction and purification techniques at a cost of 40 thousand dollars per milligram. Once the genetically engineered interferon-producing bacteria developed recently are available in commercial quantities, the price per milligram is expected to be about 10 cents. Genetically engineered interferon has already been tested on humans with some success, and it is expected to be on the market in a few years.

However, that spectacular early success of genetic engineering in biomedicine occurred for several reasons that may not be typical of other applications. First, the substances produced thus far are "one-gene" products—the genetic material responsible for their manufacture can be readily inserted into bacteria, which then can reproduce rapidly in fermentation tanks. Second, money for research and development in this area, both private and Federal, has been readily available. Finally, there exists an active community of highly skilled researchers, trained both in recombinant DNA technology and in biomedical research, who are strongly motivated to develop approaches with the potential of curing a variety of genetically determined diseases.

Nonetheless, a number of commercially valuable biomedical products already made in the laboratory by recombinant DNA techniques will go into production soon. They include human insulin, human growth hormone, interferon, and a vaccine for hoof-and-mouth disease. It is thought that many other therapeutically useful products will be made possible by the technology and that the commercial availability of such products is simply a matter of time.

Genetic engineering not only will make possible the production of useful substances at affordable prices, but it also is expected to facilitate the development of far more precise methods for detecting genetic diseases in utero. While it is still too early to know how successful such gene therapy will be, there are, in theory, no insurmountable technical obstacles to the diagnosis and treatment of genetic disease at the cellular level. However, no successful experiments involving laboratory animals have yet been reported, and clinical trials with human subjects cannot proceed until clear-cut successes are achieved with animals and the potential risks to humans are adequately identified. In any case, the limitation of gene therapy is expected to be found not in the application of the technology itself, but in the ability of the genetically repaired cells to multiply successfully enough to render insignificant the proportion of still-diseased cells and, thus, to ameliorate or eliminate the disease.

Several areas of industrial chemical production are expected to be transformed by genetic engineering techniques. Industrial chemicals can be produced either by fermentation (biological synthesis) or by chemical synthesis. Essential ingredients are petrochemicals, which provide the feedstock, and heat and pressure, which are required to overcome the energy activation barriers and to speed reactions. The high cost of fossil fuels provides a great incentive to develop fermentation methods for synthesizing industrial chemicals. Also, biological processes require less energy, are far more product-specific, and are thought to pollute less than present chemical production techniques.

Agriculture stands to benefit greatly from applications of the new technology. In theory, genetically engineered plants can be made to fix their own nitrogen, eliminating the need for the energy-intensive and costly ammonia-based fertilizers on which most of U.S. agriculture and virtually all of the "Green Revolution" of the third world so heavily depend. It is thought that plants eventually can be modified through genetic engineering to flourish in salty water, extreme heat or cold, short growing seasons, and other adverse conditions. Success would open great tracts of previously unusable planting sites to agricultural production and development.

While genetically engineered plants of commercial value have yet to be developed, the fact that such companies as Shell, Occidental, Atlantic-Richfield, Sandoz, Upjohn, Pfizer, and Ciba-Geigy have established so-called agrigenetic programs suggests the seriousness of corporate interest in the future of genetic engineering in agriculture. At present, advances are handicapped by gaps in fundamental knowledge of plant physiology at the molecular level, particularly with regard to genetic traits of agricultural importance. Perhaps partly for that reason, some of the major seed companies are not yet moving into the new technology, and classical plant breeding techniques will continue to be important for the foreseeable future. In the international arena, U.S. product goals often overlap with those of overseas companies, and joint venturing and multinational licensing are becoming increasingly common. One reason U.S. scientists and institutions are now affiliating themselves with foreign companies is because there tend to be fewer constraints on research, development, and marketing of products outside the United States.

At the moment, the United States leads in the fundamental science of genetic manipulation, but that lead could be shortlived due to heavy international competition. Furthermore, the United States lags behind Japan and, to a lesser extent, Europe in fermentation technology. For example, Japan holds 80 percent of the patents in the fermentation industry and is a world leader in the production of antibiotics and enzymes. However, Japan has not yet established an organized thrust into research on applications of genetic engineering and will most likely rely on others to do so, at least in the short term. By contrast, a number of European countries, including England, France, Switzerland, and Germany, are actively pursuing programs in genetic technology and have established research and testing companies in applied genetics.

The Development of the Commercial Enterprise

In 1971, a group of scientists and investors, recognizing the potential commercial importance of developing improved strains of microorganisms for use in the preparation of pharmaceuticals, formed the first company specifically addressed to such developments. The company, Cetus, Inc., applied advanced technology to look through vast numbers of random mutations in the hopes of finding commercially promising ones.

Two years later, in 1973, Professors Boyer, at the University of California, and Cohen, at Stanford University, invented techniques for splicing together genetic material from two different life forms. By removing a section of DNA from one species and combining it with DNA from another, they efficiently created their own aimed-for variants.

Through that discovery, a new industry was created. By 1975, Cetus and several other companies were exploring the vast potential of the new field. Today there are approximately 100 small firms and numerous divisions of established companies applying the techniques of gene manipulation to produce commercially valuable products, many of which are otherwise unavailable or available only in limited quantities at high costs.

While the original scientific accomplishments achieved through intensive research were supported by the Federal Government, the development of genetic engineering as an industry has been richly aided by money from the private sector. As of 1981, approximately $400 million of private capital, not including public stock offerings, had been invested in 25 companies. Venture capital firms have played a major role in funding the startup of many research-oriented firms and have provided financial, organizational, and marketing skills. In 1980 alone, about $100 million was invested by venture capital firms. Large corporations in the drug, oil, chemical, and agricultural industries have invested about $250 million plus management consulting efforts in small research companies, an efficient way to gain entry to the field. In addition, two of the leading companies, Cetus and Genentech, have raised $130 million and $36 million, respectively, through recent public stock offerings.

However, it is expected that the rate of new investment in genetic engineering by venture capital firms will decline. Such firms probably have already made their commitments to the field. Since most products are still a long way from the marketplace, a return on investment based on actual sales is unlikely for most in the short term. Future funding for the already-established small companies will likely come from stock sales to the public and from continued investments by large corporations. Those changes in funding patterns do not mean necessarily that the number of startups will drastically drop, since companies catering to specialty markets will no doubt continue to be formed.

Yet the application of recombinant DNA methods and genetic engineering research has not been the exclusive domain of small entrepreneurial firms. In addition to those already mentioned that are active in the agricultural area, a number of other large, established corporations are developing their own serious in-house efforts. They include Merck, Hoffman & La Roche, Eli Lily, Du Pont, General Electric, and J.D. Searle. An example of a successful endeavor by a major corporation is the recently developed and patented bacterium that can decompose oil to aid in the cleanup of spills. That new life form was developed at General Electric using a combination of early genetic engineering techniques.

Clearly, the range of applications possible in genetic engineering is broad enough and is developing fast enough that both large and small commercial enterprises can continue to flourish. Nonetheless, it is expected that eventually the major firms are likely to take over large-scale production efforts, while the smaller firms cater to demands for specialty products and develop new substances for trial or clinical evaluation.

Industry/University Cooperation

Basic research conducted in university laboratories was primarily responsible for creating the genetic engineering industry, and academia no doubt will continue to play a crucial role in its development. Though the technology is in its infancy, the theoretical knowledge base on which it depends is growing rapidly. In other areas, when a new industrial technology emerges from science, there usually has been a sizable gap between the results achieved in the research laboratory and the development of practical applications. While full-scale manufacturing of useful products is largely in the future, the initial application of the results of university experiments in genetic engineering has been almost immediate. There is, consequently, great demand by both small and large firms for close collaboration with university scientists and their students.

Collaboration between the two sectors has become extensive. Some university faculty members, who are active researchers in genetic science, have some form of financial connection with one or more of the relevant commercial ventures. Others share ownership in newly formed entrepreneurial firms, participate on corporate scientific boards, or are consultants for the industry. For those who have involved themselves in the private sector, those roles have become a significant part of their professional activities. Some have even left the university altogether for positions in industry, where salaries are higher, and research facilities are often more elaborate and up to date. If the exodus from the university becomes a trend, it could threaten the continued education and training of new, vitally needed entrants in the field.

Industrial organizations have also provided funds to enable universities to expand their research activities. Some recent examples of major financial interactions have been discussed widely and often critically. Harvard University recently decided to forego participation in a direct contract with Du Pont for the sharing of research activity in genetic engineering. Subsequently, a somewhat different arrangement, involving a grant by Du Pont of $6 million, was agreed upon by the Harvard Medical School.

Hoechst & Company, a West German chemical firm, entered into a $50 million, 10-year contract with Massachusetts General Hospital, a teaching hospital for Harvard Medical School, to help develop teaching and research in genetic engineering. While the research is not to be product-oriented, any proprietary rights that develop will belong to Hoechst. In addition, the Massachusetts Institute of Technology has recently accepted a sizable contribution from a Greenwich, Connecticut, industrialist, Edwin C. Whitehead, to establish next to the university an independent institute for biomedical research, which will be engaged in part in genetic engineering research. These are only three examples of the wide variety of university-industry arrangements being considered, designed, or implemented at numerous academic sites around the Nation.

Such interactions have been viewed with mixed emotions by some in the academic community and government agencies as well. Intimate industrial involvement with university research has occasionally been referred to as a "Faustian bargain." The university's role is to foster free and independent research by faculty and students in the quest for knowledge and to disseminate openly to society the results of that research. Industry, on the other hand, is concerned primarily with profits. Unless other mechanisms are devised, industry focuses on product-oriented research and protects, through proprietary or trade secrecy, the information its researchers discover. Since those goals seem incompatible, a university's acceptance of industrial money has been viewed by some as jeopardizing its essential research role, and academicians are beginning to worry that university research may, with industrial support, become closed and too narrowly product oriented.

Some of the concerns being raised are far more subtle: Will there be, perhaps, subconscious pressures on researchers and their graduate students to change their priorities to favor investigations with higher commercial rather than intellectual potential? Will free communication with colleagues outside the commercially supported institute or center be subtly compromised? Will the "honeymoon period" that currently characterizes university-industry arrangements gradually turn sour as the differences in expectations of the two sides become more apparent?

However, other academic disciplines, physics and electrical engineering in particular, have faced the same challenges without being unduly compromised. The birth of genetic engineering has been compared to the previous emergence of computer technology or of laser and semiconductor science from university laboratories two and three decades ago. There were some problems, but fruitful cooperation was the predominant result. In addition, it should be noted that a number of industrial laboratories have a good history of conducting open, fundamental science themselves and of interacting well with universities.

However, genetic engineering is different in some rather important ways from the university-industry cooperative development of lasers and semiconductors. In those fields, even at the beginning, industry was independently facile with the new science and hence not as dependent on academic participation. Furthermore, the path from university research to actual use and extensive commercial application took substantially longer than appears to be the case with genetic engineering.

Possible solutions to the potential or existing conflicts inherent in university-industry cooperative agreements include: providing for the free and open publication of results, once patentability has been reviewed; vesting patent ownership in the university (possibly in partnership with the faculty researcher); and giving the industrial sponsor exclusive royalty, a free right to practice the patent, and sublicensing privileges. While such solutions could never be institutionalized, general discussion of the issues by the corporate and academic communities could save interested parties from having to handle such problems on a time consuming, case-by-case basis.

The Federal Government has an important role to play in providing a base of support for the most fundamental research upon which university and industry researchers then can build. It is noteworthy that when university-industry interaction in laser and semiconductor science was so fruitful, Federal support for the fundamental, basic research component of laser and semiconductor science was plentiful. Thus, the Federal Government can be quite critically involved in encouraging a healthy coupling between the university and industry. The recently enacted Patent and Trademark Amendment Act of 1980 is a good example. It stimulates applications and effective industry cooperation by allowing the rights on inventions stemming from federally supported research to be given to universities or small businesses. Perhaps most important, the act permits the granting of exclusive licenses under certain specified conditions. At times exclusivity can be a crucial factor in providing incentive for commercial development of a patent originating in a university lab. It should be noted, however, that the burgeoning genetic engineering industry would probably not have been possible without the changes in patent policy introduced by the National Institutes of Health (NIH) in 1977. It was the new NIH patent policy that enabled universities to own patents based on NIH-supported work and to license them exclusively to commercial firms for development.

Legal Issues

The patentability of manmade life forms or scientific techniques involving life processes is not obvious. Although there is some precedent derived from the patentability of plant hybrids, it was only in 1980 that the first patent of a genetically engineered life form was granted in a narrow 5-4 decision of the Supreme Court. The case was an appeal of the initial rejection of the patent for General Electric's oil-decomposing bacterium. Shortly thereafter, Professors Boyer and Cohen were awarded the patent for their 1973 basic gene-splicing technique. Those two patent awards establish that not only the organisms created by genetic manipulation, but also the general techniques or processes themselves, are eligible for patent protection. Yet, it is expected that the application of the present laws to the new techniques will be beset with confusion.

A basic problem in patenting living things is the intrinsic variability and complexity of organisms and life processes. It will be exceedingly difficult to be sure what constitutes patent infringement. When one has a patent on a specific microorganism, it may be quite difficult to say whether another's organism is or is not a descendant—or even, for that matter, whether it is identical. Once an organism, no matter how difficult to create, is out of the lab, it can readily be grown in a suitable culture. The problem will be particularly acute in agriculture, where seed is widely disseminated. The breadth of the validity of patents on genetically engineered products will continue to be challenged. Furthermore, spontaneous mutations can and do occur in nature, and they will further complicate the entire issue. In addition, international law may play a role, given the degree of foreign and domestic cooperation in the new techniques.

The uncertainty is a serious concern for people in the industry. Patent law determines to a significant extent the commercial value of technical discoveries and, therefore, some of the motivation to seek such knowledge. Patent law also helps determine the timing and nature of technical publication and the extent of proprietary information or trade secrecy.

Some decades ago, the patent laws were modified by Congress to include specially bred plants. It seems reasonable to consider now whether another modification may be in order. A potential solution would be the establishment of an interdisciplinary committee including scientists, legislators, and attorneys that is overseen by the National Academy of Sciences and charged with sorting out the rational options in preparation for legislative consideration.

Technical Personnel

If the industry based on genetic engineering technology is to develop and grow in the United States, it will require a substantial pool of highly trained people in several scientific and engineering disciplines. Molecular biologists, cell biologists, plant geneticists, and plant physiologists are all central to the field. Physical and analytic chemists and biochemists will be needed to perfect the laboratory processes. As the movement to commercial production takes place, biochemical engineers, process engineers, and experts in fermentation techniques also will be needed in large numbers.

The educational level required of such people is exceedingly high. Almost 20 percent (some 300) of the employees of the top 10 research companies started between 1975 and 1979 have Ph.D. degrees. With increasingly intensive activity in the agricultural and chemical markets, the availability of people with the required skills soon may be taxed sorely. Some believe that the most critical personnel shortages will be in the agricultural areas, and individuals with scientific and engineering background in fermentation technology will be in especially short supply.

Industry draws its research teams and its other highly skilled professionals from the research universities. The increasingly heavy demand by industry poses a considerable challenge, and universities will meet it only with difficulty. First, support for graduate students is dwindling. Second, faculty and postdoctoral research scientists who train students are being drawn to the industrial laboratories by higher salaries and more elaborate instrumentation. One possible solution would be the implementation of innovative joint university-industry teaching programs in which students spend a period of time doing research in an industrial setting as part of a degree program. That could help offset the decrease in training grants available to graduate students and persuade U.S. students not to go overseas for their education. While the actual outcome is difficult to assess, it is clear that without adequate numbers of highly trained people the growth of the industry in the United States will be slowed seriously.

Hazards and Social Anxieties

The techniques of splicing one organism's genetic material into another allow creation of new species, types that may never have come about through natural processes. Recognition that certain risks may be associated with the processes has induced concern among researchers and the public that a hazardous organism might be created, released unwittingly, and spread uncontrollably. The potential danger of such an occurrence originally appeared far greater than that posed by hazardous chemicals, since in theory a microscopic amount of the released organism could multiply undetected throughout the environment.

Adding to the intensity of the concern was the fact that a large fraction of the experiments conducted in the mid-1970s used *E. coli* as the host organism into which DNA from other species was introduced. *E. coli*, a bacterium that normally resides benignly in the human intestinal tract, is the most thoroughly understood of all bacteria, and for that reason it has long been the laboratory guinea pig of microbiology. Nonetheless, it was feared that if a pathogenic strain of *E. coli* were created, the new organism might escape into the environment and cause an epidemic of unprecedented proportions. That was of particularly great concern since genes affecting antibiotic resistance and tumor formation were targets of research at the time, and no previous experiments of that kind had ever been conducted.

Several scientists, including Paul Berg, who won the 1980 Nobel Prize in Chemistry for his research on genetic manipulation methodology, voluntarily halted some of their own experiments and initiated a public debate on the issue. The forum that received the most attention was a meeting of the leading genetics researchers, to which the press was invited, at Asilomar, California, in 1975. In response to a statement negotiated and adopted by those attending the Asilomar Conference, the National Institutes of Health promulgated a set of guidelines for the conduct of genetic manipulation experiments. The guidelines classified experiments into four hazard levels and specified the precautions to be taken at each level. All scientists funded by NIH were required to comply. Although research conducted in industrial laboratories did not officially come under the injunction, essentially all researchers in the United States voluntarily complied with the guidelines.

Work conducted since the establishment of the NIH guidelines has greatly improved understanding of the potential hazards associated with genetic engineering. In fact, experiments sponsored by NIH have even established the risk parameters for certain types of activity. A great deal of evidence exists today that genetic manipulation experiments are probably not as dangerous as was feared originally, although a continual reevaluation of the risks will be needed for all existing and future projects.

There are two basic reasons for the relaxation of concern, especially among researchers. First, attenuated strains of *E. coli* were developed. They do not survive outside the laboratory and can grow only under special conditions. The attenuated strains are now widely available as the hosts for gene insertion. Second, it is now understood that there is a basic difference between the structure of the genes of higher organisms and the genes of bacteria, a difference that prevents the lower organisms from expressing genes of higher organisms and vice versa. The incompatibility can be circumvented, but only with difficulty. It would not come about accidentally, as had been feared. There remains, of course, the possibility that a person with high technical competence, working either alone or in a team, could intentionally set out to do mischief. That is, however, equally true in many other areas of scientific inquiry; the problem is not unique to genetic engineering.

A number of researchers are now asking for a reduction in the stringency of the NIH guidelines or for their complete rescission. The procedures mandated by the guidelines can be quite expensive and can slow research progress. To the extent that the guidelines have become unnecessary, they are surely worth eliminating; however, an in-depth assessment of the guidelines and their impact is needed before any action is taken.

An advisory committee to NIH recently recommended that the guidelines all but be removed. The recommendations specified that any guidelines be enforced through peer pressure. The committee further recommended that university biosafety committees, to which all proposed gene manipulation experiments now must be submitted for approval, no longer be required. The NIH Recombinant DNA Advisory Committee reconsidered those recommendations in early 1982 and voted to retain mandatory Federal controls on gene-splicing research while somewhat relaxing their provisions. Most researchers appear to support the advisory committee's recommendations, but a minority have expressed strong reservations. While the dissenters agree that the hazards are less than were once feared, they would prefer to move slowly until much more is understood.

Potential hazards to human health are at the center of most of the concerns, including those that have been the subject of the NIH advisory committee recommendations on existing NIH guidelines. That is appropriate, since most of the research on genetic manipulation so far has dealt with organisms that could eventually affect humans. However, there is growing interest in applying genetic engineering to problems in agriculture—in particular, to improving plants. Although plant scientists seem to be somewhat less concerned than biomedical researchers about the applications of genetic engineering, the same cautious approach seems appropriate. Researchers now are concerned with the potential loss of genetic diversity, through the impoverishment of the gene pool, if a greatly accelerated move toward monocultures were to follow successful genetic engineering. The destruction of genetic diversity could result in an increased susceptibility to pests and an ever-increasing use of chemical pesticides to compensate. The formation of a study group, perhaps within the Department of Agriculture, to develop a knowledge base, assess problems, and devise strategies appears to be a reasonable first step.

There is danger of public misperceptions of both actual potential hazards and unwarranted anxieties. Any restrictions or relaxation of restrictions must be adopted in a manner that will maintain public confidence. Even a minor incident would lead to a revival of earlier fears. Local ordinances, based on inadequate information and attempting to regulate genetic engineering research, could impede the development of the industry and have particularly severe impacts on researchers and laboratories. Some cities already have enacted such legislation. Yet the issues raised by genetic engineering are not readily amenable to solutions on a local level. To help avoid the proliferation of local actions, the public should be invited to participate in informed discussions of the issues. In that way, decisions can be based on the most reliable information, and some national uniformity can be achieved.

Federal Support

Substantial fractions of modern technology, health care, and agriculture can trace their origins to research supported by Federal funds. Rarely, however, has there been an example as clear-cut as genetic engineering. Only a few years ago, virtually that entire field of research in the United States was federally supported. Nonetheless, there were critics who argued that the Federal Government was wasting millions to satisfy the curiosity of molecular biologists, with no prospect of useful output. There is every reason to believe that a decade from now genetic engineering will be a prospering and socially beneficial technology with vastly greater payoffs than the total research investment.

The Federal Government has accepted the responsibility for supporting research focused on acquiring new knowledge. Most of the basic research activity in genetic engineering today clearly falls into that category. However, when research has the likelihood of sufficient commercial application to attract the investment of substantial private funds, Federal funding is no longer appropriate. The area in which that funding situation is true for genetic engineering is so large that care will have to be taken to ensure that important but not readily commercializable research is not overlooked.

Of the $150 million annual budget devoted to genetic engineering research by the Federal Government through its granting agencies, most goes to universities. The National Institutes of Health, the Department of Energy, and the National Science Foundation are the major suppliers of grant funds in genetic engineering. Research funds also are available to industry through special small business innovation and research programs, through cooperative university-industry research programs, and by direct grant application. NIH has recently begun accepting grant applications from industry. However, the needs for research funding in this rapidly developing field will probably change faster than funding distribution channels can adapt.

Conclusion

The powerful technology of genetic engineering, with its recent basic science discoveries, its move to commercialization, and its recognition of and response to possible risks, has provided a gratifying example of societal advance through scientific knowledge. Any new technological development of that scope carries with it attendant problems and risks that will have to be reevaluated continually. Nonetheless, given the increasingly exciting opportunities the new field presents, one can look to the future with considerable optimism.

Industrial Robotics

Abstract

The increased attention being given to a wide range of potential applications of robotic technology arises from concern with productivity, fascination with those increasingly humanoid machines, and fears of large-scale displacement of workers. The industrial robot today is, in essence, a computer-controlled manipulator arm that is reprogrammable for a wide range of simple functions; the robot of tomorrow will have its capabilities enhanced by rudimentary tactile and visual senses. Robotics technology allows reduced labor costs, higher product quality, and improvements in the workplace as robots take over appropriate and, often, the least desirable jobs. The robot-automated manufacture of batches too small for single-purpose automated machinery and the feasibility of shifting readily from one product to another will enhance responsiveness to markets and to defense production needs. The physical and organizational changes associated with robots so far have slowed their introduction in U.S. industry, while other countries are adapting to the technology more rapidly. Nevertheless, U.S. production of robots is expected to increase at a rate of 35 percent annually, with some 120,000 estimated to be in place by 1990. That number seems to preclude major robot-induced worker displacement, although some is anticipated and should be planned for. Many feel that the net effect on employment may be positive, since jobs are created by improving productivity and enhancing the competitive position of U.S. manufacturing. Robotics is only one component of factory modernization, but it is an important and highly visible one.

Introduction

Robots built or designed today are vastly less elaborate and humanoid than the models found in science fiction. Although nothing like R2D2 of Star Wars will exist for many decades, humanoid machines are intrinsically intriguing. They excited the imagination long before the word "robot" was introduced by the Czechoslovakian playwright Capek in his 1923 play, R.U.R. (Rossum's Universal Robots). Robot simply means "worker" in the author's native language. Even the essentially machinelike robots of today are, at times, lightheartedly ascribed human feelings by their designers as well as by workers in the factories where they are used. When the possibility of robots displacing people arises, however, the anthropomorphic qualities attributed to them may escalate the emotional reaction beyond that normally caused by the introduction of other machinery. As robots become a more familiar phenomenon and their limitations are more widely recognized, the machines no doubt will be accepted simply as the next incremental development in factory automation.

Most observers take a positive view of the steady evolution of machinery, from powered looms to computers, and see improved technology as largely responsible for our modern standard of living. Industrial robots can fit naturally in the pattern if the physical and organizational changes their introduction will necessitate are adequately planned. The development of robots results from the confluence of two technologies: computers and machine tools. The blending of sophisticated mechanical design, powerful information processing equipment, and advanced software has enabled computers to control the performance of a wide variety of complex tasks.

Three somewhat overlapping phases of development characterize the evolution of robotic technology. The first phase has entailed the development of relatively simple, preprogrammed or "open loop" robots. Most present day robots are simply mechanical arms programmed by a computer. At the end of the many-jointed manipulator arm may be a clamp to pick up parts or to hold such tools as a spot-welding electrode or a paint spray gun. Information stored in a computer memory can make the arm move to any predetermined position and actuate the device fastened to its end.

In the second phase, robots with rudimentary sensing and feedback capabilities have been developed. They are essentially preprogrammed robots whose programs can be modified in minor ways through feedback from sensors. The final phase, which has not yet begun but is viewed as a highly promising area for future development, is the introduction of "closed loop" robots having extensive sensing feedback properties. In that phase, intelligent robotic systems would be able to respond to their environment, to make rudimentary judgments, and to change work commands as needed. They could be used in a wide variety of work settings. However, that phase of development is probably quite far off; the technology now stands only at the threshold of what is likely to be a long evolutionary process over many decades.

In recent months, robots have been the subject of a cover story in a leading news magazine, featured in several popular business and science publications, and discussed in a spate of articles in the daily press. Although the degree of attention they have received is probably out of proportion to their restricted capabilities and to their limited deployment likely in the near future, some serious attention is warranted.

Robotics is an important and widely applicable technology, now in the vanguard of manufacturing methods in the United States and abroad. Not surprisingly, planning for the introduction of industrial robots raises dramatically the problems of workplace reorganization and employee displacement and retraining, plus the need for new ways of thinking about factory production methods. Yet regardless of the potential labor and organizational problems associated with their introduction, incentives for the utilization of robots are strong. They include increased productivity, enhanced product quality, and more effective responses to market changes.

While advances in the technology surely will allow impressive new capabilities for robots, it is the rather limited robots in production today, or on today's drawing boards, that will have a significant impact on the manufacturing technology of the eighties. Beyond that time, uncertainty increases rapidly, and policy implications become more speculative. The primary focus of this discussion, therefore, will be on those robots likely to be entering our factories in the next decade or so.

The Technical Situation

American robots are being produced by 10 companies, of which two, Unimation (Condec) and Cincinnati Milacron, account for about 70 percent of all sales. General Electric recently has announced its entry into the field, and there is speculation that other large industrial organizations in the machinery and computer fields may enter the market in the next few years. American robot production is approximately 35 percent of the worldwide total; Japan has approximately 40 percent of the total. These figures do not include the large number of robots produced by companies for their own internal use.

As previously described, today's robot is usually a many-jointed manipulator with an "end-effector" (gripper, welder, paint sprayer, etc.) that can move in a complex preprogrammed pattern, performing its function at appropriate positions. For example, one of the simplest and earliest uses of the technology was the introduction of robots into the die casting industry in 1969. The robot's gripper removes a red hot part from the die, dips it into a cooling bath, holds it in a trimming press, disposes of it, and then repeats the process—all at a constant rate. The robot can perform that repetitive hazardous job at lower cost than a human operator can.

The major industrial application of robots today is automotive spot welding. There the robot's end-effector is a welding unit that clamps two pieces of metal in the car body together and turns on an electric current to make the weld. The robot arm then automatically moves to a new position to make the next in the series of spot-welds for which it is programmed. Different automobile models may be interspersed on the same assembly line, since the robot's memory merely has to contain the program for each model presented to it. The robot produces a higher quality series of welds more rapidly than a person can.

To program a new sequence into a robot's repertoire, the robot usually must be "taught" by switching it to a "learn" mode. Using appropriate controls on the robot, a human operator manually moves the machine through the exact sequence it will later perform automatically. Once completed manually, the new sequence becomes part of the robot's stored capability, to be selected as required. Some advanced, mechanically accurate robots can be taught a new sequence by means of a magnetic tape containing a generic program that can be followed by any robot of the same model. That eliminates the need for time-consuming manual teaching. The crucial difference between present-day robots and the now traditional machinery of "hard" automation—automatic machinery that can be used only for a particular purpose—is that robots are versatile. The recipes for many alternative, elaborate motions can be stored conveniently in the robot's computer memory. A particular recipe can be selected as needed, and new sequences can be added easily.

Robots also are being used in conjunction with other advanced machines. For example, a typical numerically controlled machine tool could be a lathe in which the operation is controlled by a form of memory (e.g., punched tape). A machine under such control can bring a series of cutting tools in contact with the workpiece to shape it in a preprogrammed fashion. Some numerically controlled machines now have robot arms that load and unload the workpiece from the machine. Such special purpose or "dedicated" robots will become increasingly common. Nevertheless, as advanced robots become more versatile and capable of more sophisticated tasks, they will also become increasingly distinct from computer-controlled machine tools.

Robots will, in the next decade, "see," "hear," "speak," and "feel" objects in a rudimentary way. They will be mechanically more facile, and they will interact with computers and computer-controlled equipment in the factory. A rudimentary form of vision, allowing a robot to "see" the object it is working on, is the capability that will most extend the potential applications of robots in the workplace. Giving a robot a TV camera "eye" is relatively simple; getting the robot to recognize objects is a far more complex task. In both industry and academia, the research effort to enable a robot to visually recognize objects is intensifying, stimulated by the increasing computing power and decreasing cost of digital electronics. Since the factory robot usually interacts with a known object, the important vision problem is the simpler one of recognizing the object's position and orientation. It may be desirable for the robot to perform that task even when the object is in a bin and partially obscured by other objects. While this job is very easy for a human, getting a machine to perform it requires extremely sophisticated computer techniques. As one leading robot designer remarked, "It makes you appreciate people." Simple specialized robot vision systems are available in the laboratory today, and it is predicted that moderately sophisticated ones will be commercially available by the middle of the decade. Refining the visual capabilities of robots will enormously enhance their applicability to test and inspection tasks.

For such operations as assembly, vision may not be as necessary as a sense of "touch." The development of that sense would enable a robot to recognize when parts are not fitting properly and to make position adjustments as needed. As with "seeing" robots, many gradations in a robot's ability to feel an object are possible. A very simple tactile sense could be quite effective in enhancing a robot's mechanical measurement accuracy, permitting less expensive mechanical construction and greater applicability to a wide range of assembly operations.

Semiconductor microelectronic parts are now available for the storage of a modest vocabulary from which specified words can be retrieved instantly. Such devices are being used to enable existing equipment to "communicate" by voice with its user. (For example, "Oil pressure is low.") Potential uses for robots include communicating maintenance needs and providing information about work progress. Although understanding speech is considerably more difficult, it is expected that robots and other equipment may be able, in the not too distant future, to respond to a limited vocabulary of well-articulated commands by an operator.

Yet, despite impressive advances, the performance of robots will remain vastly below the range of human capabilities. In the short term, certain mechanical improvements are foreseen. Today, robot "hands" have to be changed for almost every new job. Primary improvements will be made in general purpose or standardized grippers. Another needed advance is in energy efficiency. Robots today use considerably more energy than a human to perform a given job. In addition, they are more massive and occupy more space than ultimately will be necessary.

The rate at which robot capabilities are developed and adopted will be determined by the worldwide demand for new abilities in the marketplace, by the availability of people highly trained in the relevant technology, and by the financial support given to the fundamental research and development needed for advances. Where most of the research and development will occur remains an open question. Most of the original research in robotics was done in the United States, and this country remains the leader. In recent years, however, the proportion of research and development conducted in Japan and Europe has been increasing.

The factors now influencing the robotics industry are similar to those that paced the development of the computer industry. Although accurate predictions of the rate of change in robotics technology are not available, uncertainties about the technological development should not preclude planners from tackling the expected worker displacement problem so that its negative effects can be mitigated.

Impact of Robotics on Manufacturing Processes

Pressures for the use of robots are the same as for other machinery: to provide products and services to consumers at the lowest possible cost to industry. With the advent of the industrial revolution, it became possible to amplify the physical abilities of people with increasingly powerful and complex machines able to perform particularly arduous or repetitious jobs. In the last few decades, the enhancement of human intellectual facilities became a reality by programming computers to perform vast computational jobs. A blending of the two technological breakthroughs has now allowed computers to be programmed to operate machines.

Computer-operated machines have been in use for some time for highly specific purposes—the autopilot that flies an airplane is one example. Recent advances have enabled the development of highly versatile computer-controlled machines, or robots, that can take on some of the most routine or hazardous factory roles. Since many of those roles require more flexibility than previous forms of automation could address cost-effectively, the introduction of robotics was a logical step in the evolution of industrial technology.

While the justification for robot installation has usually been the labor cost savings, robots have generally been found to have such additional benefits as enhanced product quality, including greater uniformity of dimensions. The absolute regularity of the robot's work rate permits a smoothly flowing production line and the efficient operation of other machines. The robot's ability to work in environments optimal for the manufacturing process, even ones noxious to people, can also result in improved product quality and efficiency. For example, robotics makes possible the application of certain automobile paints now thought to present toxic hazards to humans. In addition, robotics results in a process advantage and a superior final product.

The functions taken over by robots are often those in which repetitive consistency of performance is a major factor. Such tasks are ideal for a robot, which, in addition to consistency of performance, does not leave the work station idle at shift changes, take breaks, or suffer fatigue. In jobs robots do especially well, the downtime required for repairs may not be significant when compared to employee absenteeism.

For a company to justify the commitment of capital to conventional automatic machinery that can be used only for a particular purpose (hard automation), very high production rates and the assurance of long production runs are required. In addition, once the commitment to hard automation is made, the design of the product is of necessity locked in, and there is great reluctance to improve or change the product until the automated equipment is fully amortized. Since most manufacturing processes do not meet those requirements, the majority are accomplished with considerable manual labor.

In certain manufacturing processes, robotics can fill the gap between the heavy commitments demanded by hard automation and the relative inefficiency of manual labor. Robots can often perform specific manufacturing procedures with almost the same efficiency as specially designed equipment, but without its inflexibility. If work on a product must be stopped, permanently or temporarily, a robot can be reprogrammed and assigned to another function. Robots also can be adjusted relatively easily for changes in product design.

The market demands a great variety of models and sizes of many types of products; consequently, approximately 80 percent of American manufacturing is done in batches too small to warrant specialized hard automation. That is especially true of the U.S. defense system, in which short and sporadic production runs result in high manufacturing costs and minimal incentives to industry to invest in production equipment. Examples also can be found in the civilian sector, where one major manufacturer of fractional horsepower electric motors supplies the motors in 4,000 models. It is predicted that robotics will have a significant effect on the economics of small-batch manufacture and may be a major determining factor in the availability of such items.

Some manufacturers and users of robots feel that robotic technology also will gradually make inroads into the province of hard automation. That would involve the assignment of sophisticated multipurpose machines to a single function, but it is likely that this action will be increasingly economical as robots develop. Robots will eventually be stock, off-the-shelf items, and it may be that an automated operation can be put together more efficiently with them than with equipment requiring special order. When automation is accomplished with robotics, such startup expenses as design and debugging can be spread to a large extent over the hundreds or thousands of identical robots that eventually will be installed in many different firms. Also, changes made during production to improve the product or to accommodate market trends can be incorporated more readily into a system assembled with a flexible robotic component. The use of many similar robots allows considerable simplification in maintenance and the stocking of spare parts. At the final stage in the life of an automated manufacturing system, robots have the advantage of not becoming obsolete as rapidly as special purpose automated equipment, since they can be assigned new roles. In effect, robotics permits the substitution of software for hardware in machine design.

In assembly operations, the fitting together of completed individual parts to form frequently used subassemblies or to complete the product is done almost entirely with manual labor. Such operations occupy a substantial fraction of the Nation's manufacturing work force, although it should be kept in mind that manufacturing only accounts for about 22 percent of all jobs in the United States and is declining steadily. A number of relatively simple assembly operations are now performed by robots. However, most assembly operations, particularly the final assembly steps with large parts and considerable customization, do not easily lend themselves to automation. Nevertheless, robots will make gradual inroads into assembly operations, especially as rudimentary vision and tactile sensing become commercially available. Since the potential for economic payoff is large, intensive efforts to introduce robotics technology into assembly operations are under way. Those efforts, which are taking place in industrial and university laboratories, include the development of both advanced robotics hardware and sophisticated computer software.

Not surprisingly, today's factories are designed with the capabilities of humans in mind. A reorganization of factory environments to accommodate robots will facilitate their adoption. For example, the finished parts that are now often dropped randomly into a bin could be placed on racks in a way that would preserve orientation and relative position throughout the manufacturing operations. That kind of reorganization would foster the introduction of robots, and the introduction of robots would in turn foster greater changes in the workplace. Modifying the factory to suit robots, of course, allows the employment of less complex, less costly robots with less elaborate programming.

The language of the robot is computer language, and eventually that fact will allow robots to communicate conveniently with the equipment of computer-aided design and computer-aided manufacture (CAD/CAM) in all stages of manufacturing. CAD programming can contain the capabilities of particular robots and provide advice to designers on the compatibility of their ideas with those capabilities. In that way, CAD programming might provide the actual program for the robot, as it does for the numerically controlled machine. Then the CAD output would be in a form that could be directly translated into a program for CAM without the human intervention of blueprints and written specifications. The robot can interact readily with the computers that monitor the overall manufacturing operation—to provide information on the number of parts processed at each station, for example. It is particuluarly important for the robot to interact in that way, since it is often the robot that links different machines and processes. As advanced computer languages become increasingly similar to normal conversation, robots will also be capable of interacting more naturally with people.

While some believe that the "unmanned factory" is the ultimate phase of robotic development, others feel that the most likely final stage is an environment shared by people and machines, with machines being predominant and used primarily to enhance worker capabilities. Examples of total automation already exist in the manufacture of machine parts in the United States, Europe, and Japan. For more labor-intensive manufacturing operations, however, the practicalities of a factory without workers are highly questionable. Nonetheless, Japan has recently reactivated its futuristic, completely automated factory system program. Valuable experience in large-scale automation coordination will no doubt be obtained from that program.

Economic Aspects and Incentives for Robotics Adoption

The United States has traditionally been at the forefront of technological innovation and development. However, during the 1970s, that technological superiority became increasingly subject to challenge in several areas. American productivity faltered, unemployment and inflation increased, and imports substantially displaced many American manufactured products. To counter that competition, American manufacturers are automating production and frequently moving labor-intensive jobs out of the country to sites where labor is cheaper and production costs can be reduced substantially.

It is thought that a significant aspect of America's decline in industrial competitiveness has been the slow pace of industrial renewal and development. Machinery in U.S. factories is significantly older than that in the factories of most Western industrial nations. Introduction of the most modern machinery has been slow, and a relatively small number of robots is now used in United States industry. The number of industrial robots in use in Japan, for example, is substantially greater than in the United States. More specifically, Japan has several thousand robots in its automobile industry, while only about 1,000 are in use in American automobile factories.

In the final analysis, the rate of adoption of robots in American factories will be determined by the competitively driven decisions of individual firms. A demonstrated cost-effectiveness of the machines, taking into account labor cost savings, product quality improvement, and flexibility to respond to fluctuating market demands, will no doubt result in considerable pressure for rapid introduction. The substantial pay increases now required for hazardous or unpleasant work will add incentive for the adoption of robots in such operations.

Most analysts predict that the growth rate in robot production will be about 35 percent annually for the rest of the decade. The United States produced about 2,000 in 1980, and that figure is expected to increase to about 40,000 per year by 1990. The growth rate will be even larger in selected industries. Currently, the largest American user of robots is General Motors, which now has over 550 of the machines and expects to be using 14,000 by 1990. The robotics market in the United States in 1990 is predicted to be between $2 and $3 billion a year. That sum is actually relatively small, constituting only about 10 percent of the predicted investment in ordinary automation equipment.

As with the majority of technological innovations, the United States has led the way in the basic research, engineering, and pilot production of robots. However, following a pattern that is becoming all too common, other countries have picked up the technology and applied it effectively enough to develop a competitive advantage. Today the United States robotics industry supplies most of the robots used in American factories, although we cannot be assured that this will continue. Japan's robot production capacity is already larger than is needed for that country's domestic requirements. Moreover, Japan's greater rate of robot introduction could give its manufacturers an advantage of economy-of-scale and expertise in the design of advanced models that may be hard for U.S. industry to overcome. There is good evidence that this has already happened in the numerically controlled machine tool market.

While top management's interest in and support of the introduction of robotics may be crucial for setting the atmosphere, the decisions are generally made at the plant manager level. That is the level at which responsibility for economically getting the product on the shipping dock of a particular plant legitimately rests. In contrast with Japan, where decisions are traditionally made on the basis of long-term corporate considerations, American managers at the plant level and, perhaps, on other levels as well tend to view a few years as a long time.

That general attitude may be partially responsible for the short payback time usually used in estimating the cost-effectiveness of installing robots in U.S. plants. The primary reason for a given robot installation is to perform a specific function in the manufacture of a product. Robots are thus considered a form of automated equipment. The payback period typically used for evaluating such purchases is quite short because automated equipment is often made obsolete by manufacturing changes required by product modification. A much longer payback period is used for more generally useful machine tools. Since robots, unlike hard automation systems, are not made obsolete by production changes, and since they relatively easily can be assigned other functions, a longer payback time seems appropriate. The problem is that while it is reasonably clear how a lathe will be used 5 years after purchase, the specific function of a versatile robot is uncertain.

When robots are introduced into existing plants, considerable changes in plant layout may be required. Because such changes may be both extensive and expensive, resistance to robot introduction is common at several organizational levels. There may also be the problem of limited availability of engineers and technicians with needed skills. Production with robots is more capital intensive than with manual labor, and it can be risky, since in times of slack demand for the product, the expense of owning the robots continues. Unlike workers, they cannot be laid off, although laying off workers is, of course, not without attendant human and financial costs.

A major new opportunity for companies and the economy at large created by robotics and ancillary forms of automation will be the changing economics of small-batch production. There will be less need to inventory items that can be produced with little setup time. Manufacturers increasingly will be able to respond economically to fluctuating market demand and, therefore, will be more willing to produce for small and highly differentiated markets.

Production of small batches is frequently the forte of small companies, which may supply subassemblies to larger organizations or address the market directly. Thus, the effect of robotics on many small companies may actually be quite positive. It is certainly within the capabilities of small companies to acquire robots. By reducing the quantities at which automated small-batch production becomes economical, robots also may allow smaller companies to conceive and to develop new products or services or to address markets too small or too specialized for larger companies. New small companies, of course, start out with new plants and escape the problems of modification and reorganization of antiquated factories in adapting to the new technology. Many small companies have a deserved reputation for flexibility and innovativeness, and frequently they will be able to avoid the institutional problems that will continue for some time to inhibit larger companies. It is noteworthy that, at present, the production and servicing of robots is done primarily by small companies.

Employment and Jobs

To some extent, the fears of labor concerning the technological displacement that the introduction of robotics is likely to cause are due to the misperception that a one-for-one replacement of a person by a robot will occur. Within the next decade or so, a major net replacement of people by robots in the work force surely will not occur. In fact, more jobs may be created than eliminated, as has been the case with other forms of automation. Studies have shown that employment increases have been greatest in those industries showing the most rapid growth in productivity and the most rapid rates of technological change. Generally, automation seems to lead to a shift from production to such nonproduction jobs as those involving maintenance, engineering, programming, or planning. Factory modernization can create new jobs through the reduction of product prices, which increases demand and helps prevent jobs being moved outside the United States to be done by cheaper labor. Nevertheless, some displacement will surely occur. The likely extent of such displacement should be assessed and its impact mitigated through retraining and more effective long-term planning for the use of human resources.

Actually, it has been predicted that far more people will be displaced in the traditional way by increases in the deployment of specialized hard automation. The numbers are not easy to project, but the anticipated expenditure rate for robots in the next decade is substantially less than one-tenth of the total for all forms of automated equipment. Furthermore, studies of the nature of blue collar manufacturing jobs estimate that only one such job in seven is a possible candidate for robotization, and the fraction of people displaced may be far less. Displacement, it should be emphasized, does not necessarily mean unemployment, which will surely be much less.

What then is the likely rate of worker displacement? The predicted high annual growth rate of 35 percent for the U.S. robotics industry means that the number of robots produced per year in 1990 would be 40,000. At that time, the number of robots then in place would be about 120,000. That total is only a tiny fraction of the U.S. blue collar work force. It is, of course, physically possible to deploy many more robots; however, the economic and institutional motivations currently are not present. Any displacement of workers by robots will be a gradual, evolutionary process.

Unemployment directly attributable to the introduction of new technology promises to be a major collective bargaining issue in the coming decade. By and large, labor and management are approaching the problems with sophistication and with the realization that it is far from a zero-sum game, in which one player's gain is the other's loss. There are modes in which both advance. Labor largely accepts the need for productivity improvement and overall employment gains, but it will press for job stability and ask for advance notice of significant changes, allowing for the opportunity to retrain workers whose tasks are discontinued by automation. Labor perspectives will be incorporated in decisions regarding automation. While some of labor's demands are likely to meet resistance from management, employers recognize the importance of cooperation on this highly sensitive issue.

Beyond improved productivity, societal benefits of robotics and automation are substantial. A major benefit is enhancement of the quality of jobs and the workplace. Jobs taken over by robots are invariably those at the bottom of any scale of desirability. Those dull, repetitive, and often hazardous jobs have largely been created by mechanization, and as society advances it is appropriate that they be taken over by machines.

Aging factories that become competitively uneconomical are often closed, blighting the local community. In some labor-intensive situations, robotics technology will be able to reverse the economic equation by flexibly fitting in with existing facilities. In contrast, specialized automation usually would not be feasible or warrant use of the original plant.

. There is a somewhat blind faith that allows our society to move ahead with machines that amplify the physical and intellectual output of workers. The faith is that those machines will not deprive people of their livelihoods but will serve to stimulate the creation of new products and services, many of which will satisfy yet unrecognized needs. History provides sound justification for that faith. The most modern example, the computer, was and to some extent still is feared as a threat to employment. The ubiquitous presence of the computer in our daily lives indicates that employment has, in fact, been created by it. Thus, today the computer is largely accepted as a machine that helps people with complex or tedious tasks. So it will be with the computer-controlled versatile mechanical manipulators called robots.

Implications for Government Action

Some other Western industrial countries have exceedingly detailed national industrial policies that specifically address the commercial development and deployment of robotics. The United States, with its traditional hands-off policy toward government involvement in private enterprise, has been the world leader, and is still the leader, in most areas of technology. Most of the actions now needed to promote industrial modernization and the development and commercialization of robotics are those that will, in general, improve the economy. It is hoped that the expectation of a reasonable return will encourage needed investment, and an expanding economy should diminish fears of technological displacement.

The present program of tax cuts, investment tax credits, accelerated depreciation allowances, and new and innovative research and development partnerships should provide significant stimulus for increased work in all phases of industrial modernization. Particularly encouraging is the new emphasis on university-industry cooperation. Federal support of relevant basic research, the results of which are not likely to accrue commercial benefits to any individual investor or firm, or in which time horizons and risks exceed those appropriate for industry, should continue and constantly be reviewed. In addition, it is necessary to find the most effective methods to transfer the knowledge gained from research supported by Federal funds to commercial and defense industries.

A further question has arisen: Are American companies placed at a disadvantage with respect to their foreign competitors by excessive or unnecessary restrictions on the corporate sharing of fundamental research and development programs and results? The implications and possible revisions of antitrust legislation and regulations should be reviewed continually.

Vocational education, and education in science and technology more generally, may benefit from greater interaction between educators and employers and from a consideration of the long-term implications of industrial modernization for young people and for those being retrained to enter the workforce. It is important to prepare people for the jobs created by new technology and not to train them for positions that will be rendered obsolete by modernization.

Robotics shares most of the opportunities and potential problems of industrial modernization as a whole. However, because of understandable public interest and consequent media attention, robotics has been a highly visible component of that enterprise. Inevitably, special attention will be focused on government actions affecting the growth of robotics.

Industrial Research, Development, and Innovation

Abstract

Recent trends, policies, and developments are expected to have an impact on industrial research, development, and innovation and implications for both the private and the public sectors. Recent initiatives in Federal tax structure, regulations, patent and antitrust guidelines, and technology transfer have been designed, in part, as incentives to stimulate industrial investments in research and development and to facilitate the removal of barriers to innovation. Industry has also initiated cooperative R&D mechanisms (for example, industry consortia, university-industry arrangements) and taken other steps to respond to the technological challenge posed by foreign competition and the economic realities of the 1980s.

It is still too early to judge the effect those initiatives will have. However, some industry experts and observers feel they will not be sufficient because current returns to particular firms on R&D investments often do not warrant taking long-term risks. Uncertainty about future economic conditions, high interest rates, and the diversion of a proportion of R&D funds to cope with Federal regulations are major disincentives to such risk taking. In addition, the urgency of foreign competition forces rapid technological change in the U.S. market and is an additional incentive for short-term R&D.

The nation's commitment to a free market economy has reduced Federal support for R&D, especially in applied research, development, and demonstration, traditionally areas leading toward commercial products. The exception is in areas where the Federal Government is the prime consumer of the output (for example, defense and space). Nevertheless, the support other governments give to R&D is often targeted to penetrate U.S. markets and presents a serious challenge to U.S. firms.

Because the relationships between government policies and corporate decisionmaking, and between R&D investments and innovation, are complex, it is difficult to devise foolproof Federal policies for stimulating industrial R&D and innovation. Nevertheless, Federal policy areas that may directly affect industrial R&D and innovation include:

- overall fiscal and monetary policy as it affects the predictability of economic trends and the cost of capital;
- tax and other incentives to stimulate private returns on R&D and innovation;
- support of research and advanced graduate work in training institutions for engineers and technical personnel;
- government procurement criteria and practices;
- foreign policy (for example, export controls on technology imposed to safeguard national security, international collaboration in R&D, and technical aid to developing countries).

Given the extensive analyses that have been conducted, the present challenge to policymakers may be to achieve consistency and stability in policymaking and to consider proposed or existing initiatives to particular industrial sectors. Clearly, such an emphasis would require greater knowledge of and attention to the sectoral, industrial, regional, international, and institutional implications of government policies.

Introduction

The prosperity and security, as well as the international stature and competitiveness of the Nation, depend upon the steady growth of industrial productivity. Growth in industrial productivity requires the continuous introduction of advanced concepts, processes, and technologies leading to new products, new processes, and whole new industries.

Unfortunately, while innovations in some industrial sectors remain impressive, the overall rate of growth in U.S. industrial productivity is decreasing. In most other industrialized countries it is rising. One significant reason for the lag in innovation and productivity in some sectors of U.S. industry appears to be a less than adequate rate of investment by industry in long-term scientific research. The Federal involvement in the stimulation of industrial R&D has traditionally been based on three categories of Federal responsibilities: direct Federal needs (e.g., defense and space), specific national priorities (e.g., nuclear development), and general economic and social needs (e.g., where the social returns derived from R&D are high, but particular innovators do not benefit enough to induce an optimal level of innovation).

While there is no doubt that technological innovation must build upon the results of scientific research, we still lack the knowledge that would allow us to trace, with certainty, all the relationships in the complex process leading from fundamental research through technological development to the production of marketable products. What is certain, however, is that industry, not government, has the necessary experience and incentive to relate research and development programs to marketing strategies. Moreover, the activities that constitute industrial R&D and industrial innovation are highly diverse and disaggregated. For these reasons, the most effective Federal actions to stimulate greater long-term industrial investments in R&D are those that remove, where possible, potential barriers to such investment rather than those actions that intervene directly in the market.

Uncertainties about future Federal policies on taxes, patents, antitrust interpretations, and regulatory requirements, as well as the high cost of capital and the general, prevailing economic environment, have been principal barriers inhibiting long-term investments in industrial R&D. The President's Comprehensive Program for Economic Revitalization, by reducing the uncertainties and improving the overall economic environment, should increase the willingness of the private sector to make necessary investments. The Economic Recovery Tax Act of 1981 contained R&D tax credits, accelerated depreciation schedules, and other incentives designed to stimulate increased corporate investment in research, development, and innovation. It has been estimated that incentives under that act and other Administration actions will stimulate an additional $3 billion in corporate R&D spending over the next 5 years. Additionally, the Administration supports pending patent reform legislation that assigns to private organizations the rights to patents developed under Federal R&D funding. It is thought that the patent reform would remove a major disincentive to participation in important national R&D efforts by a broad array of highly skilled industrial scientists and engineers.

The Administration has also focused sharply on regulatory reform as a means for encouraging greater industrial productivity. On February 17, 1981, the President issued an Executive Order calling for greater precision in assessing both the need for and the potential impacts of a broad class of Federal regulations. Subsequently, a broad-gauged study under the auspices of the President's Task Force on Regulatory Relief (chaired by the Vice President) was initiated. An important step in rationalizing regulation will be to increase the reliability of the scientific and technical information and the analytical methods on which estimates of environmental, health, and safety regulations are based. One of the primary objectives of regulatory reform is to reduce the overall industrial burden of compliance with unnecessary and often uncertain regulations. Equally important, it is hoped that the reforms will reduce the amount of R&D that has been targeted toward compliance activities and diverted from more productive innovations.

It is still too early to judge the impacts of those initiatives. Some industry experts and observers believe they will be beneficial but probably insufficient, since returns to particular firms on R&D investments do not warrant taking long-term risks under present conditions, despite evidence of long-term private benefits. Other trends perceived as detrimental to U.S. innovation include foreign governments' aid to targeted industries, decline in the availability of U.S. technical education, and increasing scope and complexity of research. Each is discussed briefly below.

Foreign Governments' Aid to Targeted Industries

Japan and some nations of Western Europe (notably West Germany and France) have targeted specific technological product areas for exports. The target industry strategy in Japan, for instance, means coordinated government support and industrial efforts to develop specific product lines for world as well as national markets. Government supports have included access to capital, government funding for basic and applied R&D, and favorable import/export policies and financing. The basic commitment of the United States to a free market system precludes that type of planned nationwide industrial policy for the private sector. Industrial policy in the United States essentially has been reactive, responsive to firms or regions suffering from foreign competition (for example, the aircraft and automotive industries).

Decline in Technical Education Capacity

Disturbing signs that the Nation's engineering and other technical training institutions are in decline include the loss of many professors to industry, especially in certain disciplines (for instance, engineering and computer science); a shortage of U.S. graduate students, particularly at the Ph.D. level, in technical disciplines (foreign students often make up half or more of the enrollments); and the obsolescence of laboratory equipment. None of those trends alone may be critical, but taken together they signal a potential erosion in the knowledge base on which innovation is built and through which it must be implemented. As the skills required to manage innovation grow more complex, the problems may become even more critical.

Increasing Scope and Complexity of Research

The U.S. science and technology establishment is still second to none. In the face of recent unfavorable trends in competition with other industrial nations for certain technological markets, however, some concern has been expressed that the United States is not allocating an adequate share of its Gross National Product to R&D and is allowing its lead in R&D over Japan and West Germany to narrow. Industrial basic research in the United States declined during the 1970s, as measured in constant dollars. That deceleration in investment comes at a time when R&D is becoming increasingly sophisticated, complex, and costly. Large capital investments are required for such R&D projects as the conversion of coal to liquid fuels. The training required for scientists, engineers, and technical personnel has also expanded, increasing the need for resources devoted to communication and management. Given constrained budgets, there may be a continual shrinking of the R&D opportunities undertaken.

Yet one should be cautious in attributing the lag in innovation to these three trends alone, since there are inherent uncertainties in tracing the relationship between fundamental research and the development of commercial products. Given the long leadtime between research and its results or payoffs and the imprecision and confidentiality that surround commercial R&D, particularly expenditures by foreign firms and governments, the trends themselves are far from clear.

Policy Implications and Options

The relationship between Federal policy and industrial decisionmaking is influenced by a variety of factors. Thus, formulating a coherent set of Federal policies for stimulating U.S. R&D and innovation is highly problematic. As noted, the U.S. commitment to a free market system has generally kept the Federal Government from intervening in development or commercialization of R&D, except in areas where the Federal Government is the prime consumer (defense and space) or where a judgment of national priority is made (nuclear energy). Nevertheless, the support that other governments give R&D in specific industrial sectors challenges U.S. companies in those sectors as well as the Nation's international competitiveness; it may therefore affect broader national interests. The Federal policy areas thought to have an influence on U.S. industrial R&D and innovation are discussed briefly below.

Fiscal, Monetary, and Regulatory Controls

Without hesitation, industrial managers cite uncertainty about fiscal, monetary, and regulatory policies as a leading deterrent to long-term investments in R&D. High interest rates discourage long-term R&D investments, particularly in those technologies that are less understood and where payback rates and periods cannot be estimated reliably. The R&D conducted under such circumstances is likely to be conventional and incremental rather than truly innovative.

In environmental, health, and safety regulation, or even in more traditional forms of commercial regulation, the concern is not so much the overall necessity for regulation as its unpredictability. Critics also claim that the regulatory process is often so cumbersome and arbitrary that it adds unnecessarily to the time and cost required to introduce a new product.

Tax and Other Incentives

Government incentives to stimulate innovation have been justified on the grounds that there appears to be a high ratio of social to private return in R&D leading to the commercialization of inventions. Studies suggest that social or public benefits may be twice as high as the returns realized by the innovator or company responsible for the innovation. Those findings have led to a search for options to increase the "capturability" or "appropriability" of benefits to the innovator. Among those options, some of which were implemented in the Economic Recovery Tax Act of 1981, are:

(1) Providing a new 25 percent tax credit on R&D expenditures by industry, which is expected to encourage the trend toward even greater industrial expenditures in R&D.

(2) Allowing losses by R&D firms that cannot be used for tax credits to be transferred to profitable firms, as a way of increasing capital availability.

(3) Extending the patent period up to 25 years and coupling it with a fixed dollar value. Another suggestion is to establish a single court in which patent disputes are settled. That would provide more expert and speedy adjudication of patent disputes. The value of patents, generally, has declined with the increasing pace of technological innovation. Patent policy remains a politically attractive option, however, because of the clear Federal role and the ease with which changes can be implemented.

(4) Relaxing antitrust guidelines, particularly with respect to international ventures. Restrictions on U.S. companies are more severe than those imposed by the laws of other nations on their companies; that puts U.S. subsidiaries abroad at a disadvantage.

(5) Catalyzing cooperative research projects. In areas where individual firms do not have sufficient incentive to begin such projects, the Federal Government can provide startup funds and matchmaking between associations, individual firms, and universities; such ventures should, however, be forced to stand on their own merits, apart from Federal funds, within a reasonably short period.

Areas Calling for Federal Support of R&D

The Federal Government has encouraged innovation for national purposes since the founding of the Republic. Only in recent years, however, have Federal R&D programs systematically studied the process of innovation and experimented with stimulating, on a limited basis, basic and applied research specifically directed to innovation in particular industries or industrial processes. Some of the arrangements and options for using Federal R&D programs to stimulate innovation are described below.

Further Studies on the Innovation Process. Although much has been written about the success of Japan, West Germany, and other industrial countries in focusing R&D to stimulate innovations, there is a need for analysis of specific mechanisms that might improve U.S. technology, process techniques, and product performance, particularly in response to foreign competition.

Support of the Technology Infrastructure. Support of the technology infrastructure includes government R&D for development of generic technologies where industry has insufficient incentives to do the job. Such nonproprietary technologies as manufacturing processes, measurement methods and standards, properties of materials, and interface standards (between word processors and computers, for instance) would be supported. Of particular concern are emerging technologies in manufacturing and distribution, involving applications of microelectronics and microprocessors. Those technologies are changing so rapidly that market forces and voluntary coordination programs have a hard time responding efficiently. The result is failure to take full advantage of the opportunities available—opportunities being exploited by such countries as Japan, where central coordination of applications and standards has been in place for some time. Support for the technology infrastructure can also include technology transfer and the granting of exclusive patents or licenses to those willing to commercialize technology developed with government funds. Other mechanisms include collaborative R&D, exchanges of scientific and technical personnel, and sharing unique Federal laboratories and facilities.

Federal Procurement Policies

While government procurement of hardware and technologies for its own use has led to some spinoffs that were commercial successes, several aspects of government procurement tend to discourage innovation. Examples include excessive use of design standards in areas where technology changes rapidly and renegotiation policies that have had some negative effects on a number of innovative contractors by reducing profits earned as a result of efficient performance.

International Interests

Industries in the international arena have three main concerns: regulations (e.g., antitrust, Foreign Corrupt Practices Act) on U.S. subsidiaries abroad that are more restrictive than the laws applying to indigenous firms; emphasis on foreign policy rather than commercial criteria in export financing; and general controls on the export of technology. Another concern is U.S. policy on data flows across national boundaries. This is of growing importance to the overseas markets of U.S. firms and of significance to the role of high technology in the Nation's balance of trade. It should be noted, however, that foreign governments have their own restrictive data flow policies, which impede the establishment by multinational companies of data gathering operations over telecommunications networks. It is not yet clear what options would enhance the national interest here.

Sectoral and Institutional Considerations

Given the variety of old and new mechanisms available to encourage R&D in private industry, the challenges are to achieve consistency and stability in policymaking and to consider the targeting of options to particular industrial sectors. Meeting those challenges would require greater understanding of and attention to the sectoral and institutional implications of government policy. Overall, the major consideration in deciding how much and what the Federal

Government should do is to ensure that government does not do what the private sector is better able to do for itself and, in so doing, distort market forces. The most appropriate role the Federal Government can play is one of leveraging, not brute force.

Although U.S. firms are facing competition from national governments that provide strong backing to targeted industries, industry recognizes that the U.S. government-business relationship is vastly different. There has been much debate, for instance, on whether the United States should adopt industrial policies on a sector-by-sector basis. Although that is a political decision, public and private operations could be improved by more detailed analysis of the nature and duration of current and prospective competitive forces facing U.S. industry.

More precision is needed in choosing effective mechanisms to stimulate R&D that could yield innovations. That might mean, for instance, devising different incentives for small firms than for large firms, or for high-technology firms versus less R&D-intensive firms. If decisions are not made to pursue a conscious sectoral policy with the goal of spurring innovation, such other means as tax mechanisms and the auctioning of Federal R&D support to consortia that put up the most matching funds should be considered as mechanisms for targeting incentives.

Perhaps the most difficult area for government intervention is education of the Nation's scientific and technical professionals. To what extent academia, industry, and government have responsibilities for dealing with the resource constraints faced by our Nation's universities is a key question. For without trained people, whether in engineering or in foreign languages (to absorb the increased volume of R&D information generated abroad), the quality of R&D is bound to decline, and with it the pace of innovation.

Conclusion

This paper has outlined a number of areas of concern that involve government and the private sector in determining the level and nature of industrial support for R&D and technological innovation. The economic vitality and international competitiveness of the Nation depend on a strong, innovative industrial sector. It is the policy of the Administration to strengthen the industrial sector and to stimulate its innovativeness, not through direct Federal subsidies and intervention in corporate decision-making, but through the provision of incentives and the elimination of disincentives.

Contributions of Social Science to Innovation and Productivity*

Abstract

The current debate on national productivity and innovation has largely ignored the contributions of social science. This paper discusses three trends and developments: social science as a decision aid; social science as a source of social technology; and social science as a tool for understanding innovation and productivity. Despite the possibility of such contributions, there is little utilization of social science pertaining to productivity issues. Major inhibiting factors include the nonproprietary nature of social science, the disaggregation of social science support, and the isolation of social science from decisionmaking. The continued deemphasis of social science is harmful for the Nation's knowledge base and for its efforts to achieve economic and technological revitalization.

Introduction

As the 1980s unfold, American industry will be confronted with a series of strategic decisions on how best to facilitate both economic revitalization and technological growth. In parallel, government at every level will be faced with policy and program choices on how to provide essential public services most effectively in the face of diminishing fiscal resources. While technological innovations will figure prominently in both areas of decisionmaking, it has also become increasingly clear that human, social, and institutional factors will be particularly important in the innovation process. The process of creating and deploying new technologies is not merely mechanistic; it is inherently a social process that depends heavily on human actors as well as machines. Whether one is addressing the conduct and management of research, the dissemination and marketing of new technical products, or the implementation of new manufacturing processes, social and organizational influences are involved. Social science informs us about those influences. Similarly, when government makes public investments or chooses among policy and program options, the methodological and conceptual knowledge base of the social sciences often provides essential information for use in the decisionmaking process. Thus, a major challenge, for both public and private sectors, will be the identification and implementation of mechanisms that can integrate the conceptual frameworks, findings, and methods of social science research to maximize their utility in the decisionmaking process.

An awareness of the connection between social science phenomena and economic and technological revitalization has been slow to evolve. One reason is that the relationship between national productivity and innovativeness has been studied at a rather global level. For example, consistent relationships have been found between indicators of investments in R&D and indicators of economic vitality. Although there has been debate about the meaning and operational or functional definition of some of the key indicators (for example, productivity), it is generally agreed that technological innovation is a major component in the Nation's economic competitiveness and growth.[1] Similarly, the solutions proposed for economic revitalization have focused almost exclusively on actions at the global or aggregate level. It is highly probable that changes in tax policy and regulatory mechanisms can affect innovative activity. However, it is the thesis of this paper that a predominant emphasis on such Federal policy levers to the exclusion of other potentially important and influential social factors might mask influences that have been

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used effectively by our foreign competitors and that might play key roles in stimulating U.S. productivity and innovation.

For decisionmakers to recognize on more than a superficial level that innovation is in fact a social process, they must have an awareness and an understanding of the contributions that a variety of social science disciplines can make to the process. It is the purpose of this paper to cite a few of the many significant contributions of American social science, particularly those directly linked to innovation and productivity. In addition, various issues and options relevant to increasing the contributions of the social sciences to national innovativeness and productivity will be discussed.

Trends and Developments

Although the social sciences have a basic unity of purpose in their commitment to scientific inquiry, they do not represent a homogeneous set of knowledge or activities. Several disciplines, many theoretical orientations, and a variety of methodologies come under the rubric of social science. Not all of them are relevant to the issues of innovation and productivity, particularly in the short run. For economy of presentation, this discussion will focus on three types of contributions of social science to innovation and productivity. They are:

- social science as a decision aid,
- social science as a source of social technology, and
- social science as a tool for understanding innovation and productivity.

Social Science as a Decision Aid

While the methods and procedures of the physical sciences have evolved worldwide into generally agreed upon research principles, American social sciences have developed in directions often significantly different from their European counterparts. An indirect consequence is that the United States has become a world leader in the social sciences and a net exporter of social science knowledge.

The distinctiveness and preeminence of American social sciences are due in part to their adherence to the norms and origins of science as opposed to a preoccupation with social philosophy. In contrast to its development in other nations, American social science has to a large extent been pragmatic, quantitative, and heavily involved in the development and use of rigorous research methodologies. Even when the subject matter of a particular social science research project may seem obscure to the layperson, societal benefits are often realized from the development of new methods that were employed in the inquiry. That is, the methods of the social sciences have often evolved as a byproduct of substantive research conducted in each of the disciplines. The development of this methodological capability perhaps has benefited most from Federal research funds and, not coincidentally, the methodological tools of the social sciences often have been adopted by government and industry.

Among the array of social science tools available, those of particular importance to innovation and productivity have been various decision aids, which private and public sector organizations often have used to help make major choices, including those involving new or existing technology. The decision aids run the gamut from survey research to statistical techniques to sampling theory. A unifying characteristic is that the tools are "content free" and can be applied to a wide variety of substantive problems or questions. Taken together, they illustrate a fundamental strength of basic and applied social science research: the ability to translate into scientific terms questions that in other times or places would be occasions for philosophical debates rather than empirical research. Some examples are described in the following paragraphs.

Personnel Selection and Assessment. Reliable and valid tests and measurement techniques are decision aids directly resulting from social science research. The origins of the techniques are too numerous to list, but significant uses include the selection of Army officers in World War I, the personality testing performed in Veterans Administration hospitals, and several decades of education-related achievement and ability testing. In fact, large-scale use of standardized educational tests has contributed significantly to the public's concern about educational accountability and to more informed decisions about the expenditure of public funds for education. For example, some States and school districts have published summary results of testing programs so that parents can make direct comparisons among schools and school districts and decide which schools might provide a better education for their children.

Personnel selection and assessment techniques have also yielded undeniable economic benefits and contributions to productivity. For example, a recent study[2] indicated that widespread use of a valid test to select computer programmers can result in productivity enhancement equivalent to hundreds of millions of dollars. Moreover, if the use of appropriate tests were extended across the economy, the effect could be a substantial increase in the Gross National Product.

Survey Research. Utilization of survey research methodology is a multimillion dollar activity in the American economy. Information obtained through sampling and surveys is used by business to make crucial investment decisions, by government to predict future revenue and to learn about public attitudes toward policy alternatives, and by innovators to assess the market potential of new products and services. While survey methodology probably is used more today by profitmaking firms than by academic researchers, only a small portion of the research that led to the development of the methods was originally funded by the private sector.

Program Evaluation Research. A set of methods known as program evaluation research has been particularly important in public sector innovation and productivity. The intellectual origins of the methods stem from research design, social measurements, and statistics. Collectively, those social science techniques have contributed a method by which more informed choices about the design, implementation, and workability of many types of public programs can be made. Particularly noteworthy has been the undertaking of controlled social experiments to test the relative effectiveness of major policy and program options implemented in the field. A prime example is the New Jersey guaranteed annual income experiment,[3] in which program evaluation techniques were used to assess several social welfare initiatives in the late 1960s. A savings of millions of tax dollars was achieved by using the results of that research. Similar experimental studies have been conducted in such disparate areas as criminal justice, mental health, and education, with significant long-term effects on policy.[4] Evaluation research techniques also have been used in the private sector for example, in the assessment of the assessing the relative merits of a number of marketing campaigns and executive development programs.

Technology and Risk Assessment. A major problem with some technological projects has been the inability, or unwillingness, on the part of their creators to consider the long-term risks and potential results of implementing the fruits of their efforts. Some of the more unfortunate results of such shortsightedness are becoming quite evident, for example, in toxic and hazardous waste disposal. In recent years, technology and risk assessment methods have evolved—largely from social science research—to help determine the long-term effects of various technological choices.[5] Such assessments are becoming increasingly important components of regulatory and other public policy debates. They have also affected public and private choices about investments in new technologies.

Human Factors Research. Human factors research is used extensively throughout the industrial sector in fields as diverse as aviation and power plant design. A great deal of work has gone into solving such problems as the design and placement of gauges and controls for maximum readability, interpretability, and efficiency of control—all critical elements, particularly when many lives and millions of dollars in equipment depend upon rapid and accurate human judgment and performance.[6] In a recent example involving the F-18 aircraft, the initial cockpit design prevented a high percentage of Navy pilots from reaching all the necessary controls or performing other essential tasks. With human factors specialists involved in the redesign, changes were made that may have saved the manufacturer millions of dollars and significantly improved the safety of the aircraft.

Linear Programming and Econometrics. The tools of linear programming and econometrics have been a major asset to American industry. Virtually all large firms use linear programming models as part of inventory control procedures (to minimize inventory costs while providing a smooth flow of products to customers), and they also use econometric analysis in making investment decisions. For example, when deciding whether or not to construct a new plant or pump oil from a spot where operating costs are higher than for their existing wells, the firms use econometric techniques to estimate the future market prices and quantities for their product. That kind of analysis estimates profit under various future conditions, and, if the estimates are favorable, the firm invests.

Despite such accomplishments as those just described, there are problems with both the further development of decision aids and their more effective deployment in the public and private sectors. Some of the most important research and policy issues concern deployment, implementation, and full use of available aids. American social science, though clearly preeminent, still is not being exploited adequately. As noted, the decision tools often have evolved as a byproduct of social science research, not as its main objective. Much more could be done to sharpen their precision and utility. For example, the use of controlled social experiments to study complex social/technical systems in the field is still in the developing stages. To use this powerful methodological tool more effectively, we need to be able to better define and identify functional equivalents for "independent variables" (policy or program options) and to learn how to handle the major logistical issues involved in such studies. Similarly, the need for increased precision of measurement instruments, tests, and surveys will require considerable research effort in the future.

Perhaps more crucial to the development and evolution of social science-derived decision tools will be a modification of the current practice of rarely employing the methods of the various disciplines in combination with one another. The result has been that for any given application, the methods used often reflect the disciplinary orientation of the investigator rather than the collective methodological strengths of the social sciences or the information needs of the problem at hand. A redistribution of resources may be needed to facilitate the integration of the different methodological tools stemming from past social science research with tools to be developed in the future.

Despite the wide array of decision-aid methodologies available, their use in the public and private sectors differs widely. At the same time that consumer and market research techniques are used routinely in industry, government and its contractors are often criticized for not employing human factors studies in the design of new technologies (for example, nuclear reactor control facilities). Similarly, while there have been repeated attempts either to mandate or to encourage the use of program evaluation methods by State and local governments, the actual adoption of the most rigorous methods has been rather slow.

Not only has the utilization of methods been an issue, but the use of information derived from such methods has also been problematical. For example, strategic planning in American industry increasingly has been attacked for its preoccupation with short-term gains as opposed to long-term technological change and economic growth. Yet much of the data that would be useful to informed corporate decisionmaking has been and continues to be available. Such data are simply not used as widely as they could be. In an analogous manner, government decisionmakers do not always use available evaluation and technology assessment data. That may be due in part to the fact that at the present time, there are few institutional structures within government agencies to facilitate the use of such data, and there is no institutional structure that promotes the transfer of such knowledge across government agencies. The only exception is the National Technical Information Service (NTIS), which relies heavily on the dissemination of printed reports, perhaps not the most effective mode of knowledge transfer. Further contributions of social science methodological tools may be determined in part by the development of more effective structures and incentives for their use. Given the major private and public investments in innovation and productivity, more informed decisionmaking that effectively uses relevant social science research may be warranted.

Social Science as a Source of Social Technology

Thus far, the discussion has focused on social science contributions to productivity that were largely "content free" in terms of the substantive interests of the social sciences. This section addresses some past and current contributions to innovation and productivity that originated directly from the theoretical or applied substantive concerns of the social science disciplines.

Again it should be emphasized that technology inevitably involves human and physical components. By definition, technology is applied science or a method for handling a specific technical problem. The distinction between physical technology and social technology is more academic than real. The question of whether something is a technology should revolve around whether or not its origins lie in scientific research. Many social technologies are "hard" in that they were derived from rigorous research, even if they are not associated with machine or material systems. However, most social science contributions to technological progress have been largely of the "software" type.

Physical technologies are often more easily described than social technologies. A piece of hardware that plugs in or is turned on is generally easier to explain than a complex social system.[7] Despite that difficulty, considerable advances have been made in creating and validating social technologies that have a firm grounding in scientific research, that can be replicated in many settings, and that achieve consistent positive effects. A number of innovative social technologies have made important contributions to productivity.

Worker Participation and Decisionmaking. Nearly 35 years ago,[8] in a controlled field experiment conducted by American social scientists, several groups of factory workers were given different degrees of opportunity to suggest changes in production processes. The group with the highest worker participation in decisionmaking yielded the most effective implementation of changes in manufacturing technology and the most remarkable increases in productivity. The link between participative decisionmaking and the acceptance of innovations in the workplace has been corroborated and elaborated over the years in numerous social science studies.

Paralleling those developments, American scientist W. Edward Deming was working with Japanese companies in the implementation of another technology developed in the United States—statistically based quality control. That social technology involved training production workers in rudimentary research design and statistical techniques to enable them to monitor empirically and to become more involved in the production process. Those two concepts, participative decisionmaking and quality control, evolved into a unique Japanese social technology, *quality control circles*. The effect on Japanese quality control and productivity is generally seen as considerable. For example, one researcher reports that employee suggestions for incremental changes in the manufacturing process are approximately 10 times more frequent in Japanese companies than in equivalent American firms, and they result in a much higher rate of implementation.[9] Moreover, many American companies that recently have adopted quality control circles report productivity gains and cost savings of major proportions. It seems unfortunate that although the social technology originated primarily in American social science, no institutional structure to promote its use by American managers existed.

Social science research on worker participation has generated some social technologies that have been implemented in the United States. A noteworthy example is the Scanlon system used by a few dozen U.S. companies, largely in the Midwest. Developed in the 1940s by Joseph Scanlon of the Massachusetts Institute of Technology,[10] the system had its intellectual origins in group dynamics. The pivotal feature of the approach is a joint worker-management group that evaluates suggestions for innovations in manufacturing processes, product design, or other aspects of firm practice that may have an impact on performance. If suggestions are approved and implemented, any gains in productivity are passed on to employees in the form of bonuses. The system thus combines aspects of participative decisionmaking and group financial incentives. Over the years, the Scanlon companies have been leaders in productivity and innovation.

Another instance of the application of participative concepts is that of the quality of work life (QWL) efforts in various companies. General Motors (GM) and the United Auto Workers (UAW) have been leaders.[11] Aspects of the GM/UAW program have included the involvement of workers in the design and implementation of new production technology, the increased participation and decisionmaking by workers at all organizational levels, and a variety of labor-management collaborative structures.

Reinforcement Theory and Operant Learning. A major line of research in psychology has focused on reinforcement theory and operant learning. Since such work began in the 1930s, thousands of studies have been conducted in the hope of understanding how different reward contingencies influence both animal and human social behavior. Much of the work has been basic research, but in recent years the knowledge gained has been applied to the design of complex organizations and social systems. One air freight company, for example, has used behavior modification techniques to increase its utilization of productive capacity from 45 to 90 percent, with savings of more than $2 million over a 3-year period.[12] Another practical application of reinforcement theory has been the development of programs designed to help people stop smoking, reduce harmful alcohol consumption, and lose weight.

Chronic underemployment and unemployment are significant drains on national productivity. In the past, Federal agencies assigned to address the problem have achieved mixed success at best. Recently, a group of social scientists[13] developed a social technology called a "job finding club," which involves teaching job location and retention skills to unemployed persons. The program's design rests largely on basic social science research in operant learning, modeling behavior, and the study of peer-to-peer social networks. The surprisingly low cost of placing trainees in pilot experiments was $167 per client. Moreover, participants were twice as likely to secure and retain employment as clients who were also in the study but were using traditional employment assistance programs. The Department of Labor is attempting to disseminate the results of the study nationwide.

As the previous discussion of social science decision aids suggested, a major problem in maximizing social technology's contribution to economic revitalization is utilization of results. The case of quality control circles exemplifies the low domestic use of available knowledge while, at the same time, Japanese use was extensive. Similarly, although the basic parameters of Scanlon systems have been in the research literature for years, the approach is neither well known nor widely used. In fact, it is uncommon for social technologies to achieve widespread utilization and adoption. The usual pattern is local or limited use, with a constant and often wasteful "reinvention of the wheel" in disparate settings.

One reason for the limited use is the lack of institutionalized ways to identify exemplary social technologies, that is, those with a strong research base, demonstrable benefit, and replicable procedures. While the scientific journals of the social sciences perform that function for researchers, it is difficult for relatively untrained users of social science knowledge and methods (managers in corporations or public agencies, for example) to make informed choices among useful social technology and social fads. Some Federal Government agencies whose mandates include the development of social technologies have initiated screening functions to identify exemplary projects and programs. The Joint Dissemination Review Panel in the Department of Education is an example.[14] That program routinely sifts through hundreds of educational research projects and selects, on the basis of research quality and the magnitude of positive effects on children, a small group of projects for nationwide dissemination. That institutionalized identification of exemplary social technologies is unique among Federal agencies. In virtually all other Federal agencies that support social science R&D, there is no attempt to sift through the aggregate product. Similarly, in industry, only the most progressive companies have an organizational design unit to assess the potential applicability of social technologies. Future research should focus on the identification and quality control of social technologies so that potentially valuable tools are not lost.

One reason for the low rate of private sector use of social technologies is that there are few positive incentives for industry to develop, market, or disseminate social technologies systematically on a national scale. The dissemination or marketing that exists is usually done by a network of consulting firms or by not-for-profit institutions. An example of the latter is the American Productivity Center, which has been heavily involved in disseminating various productivity-enhancing social and managerial technologies to private industry.

In contrast to investments in hardware, it is often more difficult to realize private profits from investments in social technologies. The chemical composition or circuit design of a product can usually be protected by either patents or trade secret practices, and, thus, an individual firm can market it profitably. That is not the case with social technologies. Once piloted, the critical features of a social technology are usually available in the open scientific literature. Paradoxically, the nonproprietary nature of social technologies suggests that they have the potential to raise the productivity of entire industries, not just one firm. That points to the need for the government to assume a broker role in facilitating the dissemination of social technologies.

Despite the limited private sector activity in disseminating social technology, agencies of the Federal Government also have not seen fit to engage in major programs to facilitate the transfer of social technologies, particularly to private industry. Although some mission agencies may structure dissemination and transfer efforts to their particular clientele, those efforts have been limited and quite diffuse.[15] They have focused almost exclusively on hard technology. (As noted before, education is an exception.)

Still another explanation for the paucity and underutilization of social technologies is a lack of appreciation for the length of time necessary for their development. The search for the quick technological fix, of either social or hardware technology, almost inevitably leads to disappointment. For the small number of well-validated social technologies that have evolved, the R&D stage usually took 10 or more years.[16] That period of "succession evaluation" in social technology development is similar to the R&D lags that exist in the physical sciences, and it needs to be reflected in structures for the support and use of social science. For example, it suggests the necessity for continuity and stability in research and development funding, a rarity in current practice.

Social Science as a Tool for Understanding Innovation and Productivity

A third major contribution of social science to innovation and productivity is a better understanding of the process of innovation itself. Although seldom acknowledged, virtually all of the policy debate concerning national innovation and productivity is based on information derived from social science research. Studies concerned with innovation and productivity have come from many academic disciplines and approaches, but the common underlying theme is that innovation is a social behavior. The major social science contributions to this understanding constitute a set of nonintuitive findings that have radically shifted the policy debate or changed institutional practices.

Technology Transfer Process. Social science research on the transfer/dissemination of innovative technologies has recently altered our view of what "use" of a technology means. Heretofore, technologies were assumed to be either "adopted" or "nonadopted." Now it has become clear that activities after initial adoption or purchase (i.e., implementation activities) have much more to do with whether an innovation is successfully used[17] than preadoption activities do. The organization has to adapt to the technology, and the technology often has to be adapted to the organization. Those findings have relevance for the design of technology transfer programs and are particularly important in understanding the spread of highly complex technologies and those demanding major organizational and social alterations for their deployment. For example, in the next decade it is expected that billions of dollars will be invested in office automation. Yet the implementation of office systems and their impact on work roles and job functions are little understood, despite the important role of white collar work in productivity growth.

Likewise, the complexities of implementing new manufacturing systems are not well understood, despite the long-term nature of their deployment and the heavy capital investment involved.

Firm Size. Social science research has delineated the special role played by small firms in productivity growth, employment, and technological innovation.[18] While past changes in government policy and practice tended to treat all firms as equivalent, regardless of size, that is no longer the case. Special legislation and regulatory revisions have recognized the pivotal role of small businesses and focused on increasing their opportunities.

R&D Management. A large body of information on the management of the research and development process has accumulated in the past 20 years. The literature has commented on the composition of research teams, the organizational structure of research organizations, and the relationship of R&D to such functions as marketing.[19] In some of the more innovative and productive American firms, that knowledge is used routinely to guide the research process, often with resultant increases in research productivity.

Productivity-Enhancing Technologies. Some social science activity concerned with the innovation process has focused on particular technologies that have considerable implications for national productivity. For example, a major cause of economic stagnation has been recent large increases in the cost of fossil fuel. Social science research has focused on ways of encouraging the rapid retrofitting of energy-saving heating, cooling, and building technologies.[20] Presumed market forces have not had the expected incentive effects, particularly among noncommercial users, and a more complete understanding of the lack of results may be gained by looking at social and institutional variables.

Despite progress to date, a number of research and policy questions remain. Many organizational and institutional factors that play key roles in the innovation process are not yet fully understood. For instance, while there is a need to better understand the spread of technologies, there is an even greater gap in the literature concerning a reciprocal understanding of how obsolete practices and technologies can be discarded more easily. If we could better understand that, perhaps the spread of new, more productive approaches would be enhanced.

The above comments illustrate yet another gap in our knowledge. As technologies become more complex and, at times, cause worker displacement and ancillary social dislocation (as, for example, robotics and automation do), implementation rather than adoption becomes the crucial factor in their deployment. We know little about alternative implementation strategies, whether pursued by private industry or public agencies. To reiterate the conclusion of the discussion on decision aids, it might be useful to construct social experiments to compare empirically alternative approaches to implementing major technological systems. Once again, no single firm is likely to realize significant economic benefits from such a study or series of studies, but industry as a whole clearly would benefit. Mission agencies involved in technology transfer activities would also benefit.

Likewise, we need to understand more about the intervening role that such social technologies as quality control circles and gain-sharing plans play in the implementation of hardware technologies. Do such social innovations merely yield changes in worker motivation or social communication, or do they also produce changes in tool use, production systems, and product designs? Little empirical work is available as yet on this issue. Given the current burgeoning of organizational innovations in American industry, field studies are both possible and appropriate.

Not only could structures within organizations be examined, but it would also be useful to examine structures that straddle institutions, particularly among institutions heavily involved in the innovation process. There is a prime need for greater understanding of those university-industry structures that enhance the transfer of basic and applied knowledge. The university is the primary source of most basic research in the United States. Knowledge gained from that research is, in turn, often translated into new products and processes by American industry and into more effective service delivery by government. Yet the transfer process needs considerable empirical elaboration, since the structures, incentives, and government initiatives that enhance or retard university-industry knowledge transactions remain largely a mystery.[21]

Policy Perspectives

Some of the most important policy issues pertaining to social science contributions to innovation and productivity have less to do with the level of support for social science research than with the structure and locus of that support. For example, while the productivity benefits of social science research are demonstrable, it is often difficult if not impossible for those benefits to be the sole property of a single firm. Since it is more difficult for a firm to rationalize its investment in social technologies than in other technologies, normal market forces and management decision processes may not favor adequate private sector support. Similarly, while State and local governments make considerable use of decision aids and social technologies, it is not clear that any single unit of government can justify, through cost savings alone, the R&D necessary for contributions to the field. Unless clear incentives are established for private industry and State and local governments to support social science, such support may not be forthcoming.

The responsibilities for the support and conduct of social science research are scattered across many Federal agencies, more than for any other scientific endeavor. That has both advantages and disadvantages. On one hand, it has produced a diversity of methods and substantive inquiry, which probably has strengthened the disciplines. There have also been unavoidable duplications of effort and a slower accumulation of findings generalizable across disciplines. Moreover, some distinction needs to be made between the social science research that is necessarily agency specific or mission-oriented and the research that addresses more general policy issues or initiatives. For example, technology transfer and dissemination programs are scattered across dozens of agencies. Yet many of the issues involved in administering such programs involve generic social science questions. More coherent efforts to enhance collaboration among programs would likely increase the contributions of social science to innovation and productivity.

One of the most common mistakes of policymakers in considering social science contributions is a failure to recognize that good social science, like any other scientific inquiry, takes time. Some of the worst and most embarrassing uses of social science knowledge have occurred when researchers have been forced by impatient decisionmakers to conduct quick studies and shallow analyses. To develop contributions of lasting worth, longitudinal research programs should be considered. Once again, changes in the structure and not the level of funding may be involved. A clearer specification of goals or objectives to be pursued by social science over extended time periods might also be required. Social science could perform the "soft" science equivalent of a lunar landing, but it would need an objective of similar operational specificity, an equivalent time frame in which to operate, and a commensurate level of private or public support.

With current efforts to convert categorical programs in various Federal agencies to block grants, attention should be given to what that conversion implies for the spread of social technologies and the use of decision aids and evaluation research. To what extent does the capability exist at the State and local level to develop and use data-based management and decision aids? If the development and use of social technologies to address problems in education, crime control, or welfare are delegated entirely to State and local governments, how well will they perform? How will relevant information be disseminated to appropriate agencies elsewhere? And, how can exemplary program models be identified for nationwide dissemination? Clearly, a number of intergovernmental relationships with implications for innovation and productivity need to be better understood.

The legislative branch has been a leader in the use of decision aids and methodologies derived from social science research, particularly with the establishment of the Institute for Program Evaluation in the General Accounting Office. There has been some parallel activity in the executive branch. Several agencies have policy research or program evaluation units sufficiently staffed to enable them to make methodologically rigorous studies. But such units are often isolated from agency decisionmaking, and efforts are needed to enhance opportunities for the units to contribute to program choices.

A major problem in the production and use of social science is the disaggregation of the process. In particular, there is no coordinated and institutionalized structure to engage in knowledge transfer. Usable outputs, both methods and findings, will continue to emerge from social science inquiry. However, given current structure and incentives, the Nation's use of social science and technology is likely to be constrained unnecessarily.

In summary, the policy issues confronting the Nation about social science center on how to increase more effectively the contributions that these disciplines can make to innovation and productivity. To the extent that other countries use our social science knowledge to gain economic advantages, policymakers should be concerned with the organization of domestic resources and the potential for an unfavorable balance of intellectual exchange. Support for the social sciences has accounted for a very small portion of U.S. R&D spending over the years. However, the experiences of Japan and various domestic firms serve as examples that investments in social science may produce more immediate gains in innovation and productivity than equivalent investments in the physical sciences. Thus, the most important policy issues concern the structure, locus, and nature of social science activity. A strong case has been made for considering options that might enhance the utilization of social science. Both its methodologies and its substantive results have proved their ability to increase national productivity and innovation, and they have the potential for even greater future contributions.

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Obsolescence of Scientific Instrumentation in Research Universities

Abstract

The growing obsolescence of instrumentation and facilities in the Nation's research universities is impeding the progress of fundamental research and could also have serious negative consequences in such areas of application as agriculture, biotechnology, medicine, energy, and national security. Additionally, it hinders the training of scientists, engineers, and technicians and impedes the rate of innovation by the commercial instrumentation industry. While the Federal Government will continue to offer direct support for instrumentation purchase through research grants to universities, industry and the universities themselves will have to assume a larger measure of responsibility than they have in the past for resolving the obsolescence problem.

Partial remedy could be achieved by the creation of research partnerships between industry and universities through which equipment and facilities could be shared. Another mechanism is the direct donation of instruments to universities. In both cases, the Federal Government can provide incentives (e.g., through the provision of tax credits) and thereby function in a leveraging role. Also imperative to an amelioration of the instrumentation obsolescence problem will be the improvement of university management techniques and a greater sharing of equipment within and among universities. Some universities are currently exploring such new modes of obtaining research instrumentation such as debt financing and limited partnerships.

The Magnitude of the Problem

Instrumentation and Research

The growing obsolescence of research instrumentation in the Nation's universities is a problem not just for the universities themselves, but for the nation as a whole. To the extent that such obsolescence impedes the progress of fundamental research at the university, its effects will be felt in such areas of application as agriculture, medicine, biotechnology, engineering, energy, industrial productivity, and national defense. Since over half the basic research performed in the United States is carried out at universities, a decline in university research potential could result in a significant decline in the general rate of the Nation's scientific advancement.[1]

Instrumentation is at the heart of experimental research. Modern instruments with qualitatively superior capacities for analysis and measurement can open up whole new fields of scientific inquiry and can greatly reduce the time necessary to carry out research projects. In the 1970s, for example, the development of the nuclear magnetic resonance (NMR) spectrometer and infrared spectrometers opened new areas of research in structural science. They allowed scientists to define the structure of matter with a resolution never before achieved. Further, the use of sophisticated minicomputers in conjunction with NMR now allows scientists to make measurements of molecular structure in 4 minutes that required 16 hours in the early 1970s, and previous to that time such measurements could only be approximated.[2] Access to advanced scientific instrumentation often determines whether scientists can produce ground-breaking results.

There is concern among leaders of the scientific community that instrumentation in the cost range of $100,000 to $1 million at U.S. research universities is rapidly becoming obsolete. As a result of increasing costs and decreasing sources of funds, those instruments will be difficult to replace through traditional mechanisms with the state-of-the-art equipment necessary to ensure the progress of scientific research and fulfill national needs. Because of the diversity of the problems associated with obsolescence and the different ages at which various instruments become obsolete, it is difficult to derive quantitative measures for assessing the severity of the problem. A number of studies, however, suggest that its magnitude is substantial.

Costs of Instrumentation

A 1979 Department of Health, Education, and Welfare (HEW) survey of nine universities concluded that there was an unmet need for instruments and facilities of $225 million. It also indicated that such unmet needs will persist over the next 3 to 5 years.[3] A National Science Foundation (NSF) study projects a catchup need of about $420 million for the next 5 years in the physical sciences alone.[4] A 1979 paper in *Science* showed that instrument costs have increased fourfold since 1970. That calculation did not even take into account the new technologies that have come into general use since 1970, nor the fact that the most up-to-date research equipment has an estimated lifetime of only 3 to 8 years.[5]

One recent study matched university research laboratories in a number of disciplines with nonuniversity laboratories.[6] That study found that, for the sample selected, the median age of university instrumentation was twice that of instrumentation at industrial laboratories recognized for the quality of their research. A disturbing corollary cited by the same study suggested that American universities are now becoming less well equipped than those in other countries. When asked to identify the best equipped laboratories in their fields, many researchers interviewed in the study listed facilities located abroad, particularly in Japan and Western Europe. For example, as of mid-1981, not a single top-of-the-line "super computer" was in service at a U.S. university, even though such models are located at foreign universities as well as in government and industrial laboratories in the United States and abroad.

Two factors appear to be responsible for the magnitude of the instrumentation problem: a rapid rise, well above the inflationary baseline, in the cost of the most advanced instrumentation, due mainly to the increasing sophistication of instruments required to do frontier or pioneering research; and the dwindling funds available for instrumentation at both local and Federal levels.

A study of instrumentation needs of research universities recently documented the increase in startup costs for frontier research in synthetic chemistry. Between 1970 and 1979 the costs rose at the equivalent of an annual rate of 22 percent for laboratory instruments and 23 percent for departmental instruments.[7] The same study, analyzing five important scientific disciplines, revealed that the cost of scientific instruments priced above $5,000 rose at an annual rate of 20 percent for the years from 1970 through 1978.[8] For example, the cost of a flow cytometer, an instrument with which scientists may conduct precise analyses of the chemical constituents of individual cells, approaches $175,000.[9] Multinuclear, high-field NMR spectrometers now cost up to $500,000. Furthermore, the ability to engage in frontier research requires not just individual instruments, but clusters of expensive instruments.

The costs of providing up-to-date research instruments go far beyond the price of the equipment itself. Several factors are involved:

(1) Once an instrument is purchased, additional funds are needed for its operation and maintenance. At a recent University Laboratory Managers Association meeting on October 23-24, 1981,[10] there was general agreement that the costs of equipment ownership run about 7 to 8 percent of the new cost per year. Those costs include maintenance, replacement parts, staff salaries, and equipment operation. Funds for those expenses are only infrequently included in Federal grant awards, since the funding source generally expects that the university will provide the needed maintenance. A study conducted in 1980

reported that maintenance funding in universities had become scarce, that shops for in-house maintenance were deteriorating, and that the costs of service contracts were increasing above the inflationary baseline.[11]

(2) As equipment becomes more complex and computerized, its operation, maintenance, and repairs may be beyond the abilities of researchers and students. When repairs cannot be made quickly because of a lack of available funds, essential equipment may be unusable for substantial periods, and valuable research time may thus be lost.

(3) Federal grants rarely provide for such support equipment as oscilloscopes and vacuum leak detectors, equipment not necessarily directly involved in the research itself but necessary to test, calibrate, or provide an appropriate environment for the core research instruments. Without up-to-date support equipment, research instrumentation may be far less useful.

(4) Finally, research universities must find funds to provide adequate facilities for the housing and support of instrumentation. Since the 1960s, Federal resources for the construction of facilities have been declining, placing an ever-increasing strain on institutional funds. Surveys by NSF show that Federal obligations to universities for their R&D plants dropped from $100 million to $30 million during recent years. The universities themselves have thus far been unable to fill the gap, despite the evident need to renovate and create new facilities.[12] Instrument housing costs include the construction of buildings or new wings, construction of animal facilities, renovation of plumbing and electrical systems, and installation of air-cooling units for facilities that use sensitive computers. Some of the costs arise from the need to renovate existing facilities to accommodate more sophisticated instrumentation; others become necessary because of changes in the legal or regulatory requirements for research housing.

All of the difficulties outlined above are compounded by increases in costs brought about by inflation. Thus, in a very real sense, the plight of the universities in coping with escalating instrumentation costs is tied to the health of the Nation's economy.

Effects on Training

Apart from the problems in state-of-the-art instrumentation for research and doctoral-level training, the quality of instrumentation for training engineers and technologists is also deteriorating.[13] This is especially critical for students who will eventually be employed in industry. If those students are not conversant with up-to-date equipment, costly retraining may be necessary once they are employed outside the university.

Effects on Industrial Innovation

University researchers play important roles in the development of new scientific instrumentation. Researchers often provide the specifications for special features to manufacturers, or they modify instrumentation altogether. The electron microscope was first developed by a beginning graduate student, and its development was continued for many years by university researchers. That ongoing process of development and modification at the university level eventually resulted in a powerful tool for the investigation of molecular structure. A recent study of 111 improvements in basic scientific instruments used in chemical and biological research reported that of the 44 innovations later incorporated successfully into commercial products, 81 percent had been initiated by instrument users rather than by instrument manufacturers.[14] Of the users who contributed innovations, 72 percent were employed by universities or affiliated research institutions rather than by private manufacturing firms or other organizations.

However, new instrument improvements and developments may be impeded if universities cannot afford to purchase the most advanced equipment, and the instrument industry itself may be adversely affected by the declining purchasing power of universities. Industry statistics indicate that from 1976 to 1980, sales of instruments shifted away from the educational market. In 1976, 18 percent of instruments sold went to educational users; by the third quarter of 1981 the figure had declined to 11 percent.[15] One of the major manufacturers of high-field NMR equipment reported recently that it had not had a new instrument order for a year.[16] The amount spent on instrumentation by universities has not kept up with inflation. That has resulted in manufacturers shifting their production away from the kind of state-of-the-art equipment required for research and likely to be refined by university users toward more routine instruments. The most advanced instruments then become even more expensive as fewer units are produced.

Instrument manufacturers have always participated in the production of frontier equipment with little commercial prospect in order to maintain their ties with academic scientists and stay at the forefront of their fields. As capital becomes less fluid and as universities become a smaller share of their market, manufacturers may be less likely to continue that important interaction. Consequently, already expensive handmade prototypes will no doubt become even more expensive. In addition, the transfer of new ideas from state-of-the-art equipment to general product lines will be slowed, and U.S. manufacturers may lose their international competitive edge.

Impact on Innovation Cycles

Universities have played a major role in the industrial innovation cycle for instrumentation. University personnel have joined with other entrepreneurs to form spinoff companies that carry innovative instrumentation developed at universities to commercial development. Often those companies are absorbed into larger instrument companies. Spinoff firms played major roles in the development of such modern instruments as the computerized axial tomography (CAT) scanner, a variety of other medical diagnostic instruments, and computer graphics devices. If universities are forced by dwindling resources to drop out of the innovation cycle, one means of getting needed innovations rapidly into the marketplace may be lost.

Potential Responses

The magnitude of the problem of scientific instrumentation obsolescence and the potentially negative effects the problem can have on such national objectives as economic revitalization and productivity make it of special concern for the Federal Government. That does not imply, however, that the Federal Government can or should attempt to remedy the problem on its own. It is also important to examine what the corporate sector and the universities themselves, possibly in partnership with the Federal Government, can do to help.

Corporate Funding of Research Instrumentation

Corporations and research universities find themselves beneficially interrelated in many ways. Corporations need the trained engineers and scientists that universities produce and make use of the advanced techniques that university researchers develop. Universities need the support and input of corporations in pursuing their research and training functions.

A major study of the entire array of current university-industry interactions indicates that despite differing motives, close working relationships can and do develop to the advantage of both parties.[17] One example among many is that of Purdue University, which has recently established research relationships with several corporations through its "People Exchange Program."[18] The arrangements allow university and industry scientists to work together on projects of joint interest and to learn each other's techniques while sharing sophisticated equipment.

Research relationships between universities and industrial firms are of obvious benefit to both parties. They often result in an increase in direct financial support for university research, which can be used to purchase advanced equipment. Corporations may also assist universities through the donation or sharing of equipment and through financial assistance to special funds set up for the purchase of advanced equipment. One such fund has been established at Colorado State University.[19]

There are, however, limitations on the extent and character of university-industry research relationships. On the industrial side, it is mainly the high-technology industries and agriculture that view academic science and technology as a prime source of personnel or fundamental ideas. Even in those industries it is usually only the large corporations, themselves engaged in fundamental research as well as product development, that contribute significantly to the financing of university research efforts. Furthermore, such contributions fluctuate with the fluidity of capital and the timespan of corporate planning. Currently, for most American corporations, capital is tight, and planning windows are short term.

Although precise figures are extremely difficult to collect, the current proportion of university research funded by industry is estimated at 5 percent or less. The most liberal estimates of future industrial funding of universities place that proportion at under 10 percent.[20,21] Furthermore, most corporations tend to contribute mainly to research in areas of direct immediate interest to themselves. Therefore research funding, including support for instrumentation, available from corporate sources is skewed toward engineering schools and those scientific subdisciplines likely to have the most immediate impact on product development. That leaves large segments of university research relatively unaided by industry.

Federal Leveraging of Corporate Funding

While the relationships between universities and corporations are voluntary in nature, the Federal Government can influence the conditions under which such linkages develop. Federal leveraging to increase the advantage to corporations of providing assistance to research universities is consistent with the Administration's objectives of revitalizing industry and enhancing the potential for scientific research to stimulate industrial progress through innovation and discovery. Among the mechanisms available are tax incentives or other kinds of indirect intervention, direct grant awards to university-industry partnerships, programs of support and encouragement focused on specific industries, and premarket support of innovative instrumentation development seen as essential to long-term national goals. Some of those mechanisms are described below.

Tax Incentives. Providing tax incentives for the support of research is one method by which the Federal Government may make corporate support of research efforts more attractive. Legislation recently passed by Congress provides for a 25-percent tax credit for incremental R&D expenditures, allows industries to allocate domestic R&D expenses to domestic income, and extends tax benefits for the donation of certain kinds of equipment to universities for research. While those measures are a step in the right direction, the magnitude of that step can not yet be determined. The language of the legislation is sufficiently ambiguous to necessitate interpretation by the courts in many areas. For example, companies that lease equipment to nonprofit institutions may not qualify for tax credits.[22]

In a recent *New York Times* article, Arthur Bueche, the late senior vice president for corporate technology at the General Electric Company, is quoted as saying that the legislation "biases the system in the right way, but I don't expect it to have a major stimulative effect."[23] Estimates by General Electric's tax accounting and technology staff put the savings to the company generated by the 25-percent tax credit at about 2 percent of the company's annual research budget. The same article quotes congressional estimates as showing the savings to industry from the tax benefits for equipment donations as being "less than $5 million annually." While the equipment donation provision would seem to have a more direct effect on equipment obsolescence, in the past most equipment donations have been primarily of intermediate training grade rather than state-of-the-art research equipment. Mechanisms to encourage the donation of the most sophisticated equipment are still needed.

The impact of different tax provisions on innovation and investment in research was discussed recently at an NSF-sponsored colloquium on tax policy and innovation.[24] The general conclusion of one study presented at the colloquium is that while tax incentives may have a positive effect on the level of innovation, the size of the effect cannot as yet be determined.[25] Furthermore, the study contends that tax incentives may well be ineffective when the macroeconomic climate is negative. The current economic situation may well determine the extent to which the recent tax provisions will affect corporate R&D expenditures during coming months.

There is an additional important aspect of the university-industry relationship with regard to research funding. Corporate behavior is necessarily influenced by economic fluctuations. Corporate allotments for research usually fluctuate accordingly. Yet productive research requires consistent, reliable sources of funds, particularly for equipment and maintenance. Mechanisms need to be found to prevent research efforts dependent upon university-industry linkages from being put into limbo during slow periods in the business cycle.

Direct Grant Support. There is a long Federal history of direct grant awards to university-industry partnerships. Examples include the current NSF University-Industry Cooperative Program and the former Department of Defense-DARPA Cooperative Program.[26] There has been enough experience with such general support to university-industry relations that important generalities about success and failure can be drawn. Successes have been notable in such areas as composite materials, polymer chemistry, and catalysts. Failures have been the result of many factors, including the lack of a single individual capable of seeing the project to fruition and inadequate analysis of the ability of the industry's market structure to assimilate technical advances. Such Federal project support, it should be noted, does not deal directly with the instrumentation problem, although it can indirectly improve the situation.

The University Role

University efforts to alleviate the problem have centered on improved management of available resources. Recently, two new methods of innovative financing have been tried as partial solutions to the problems of funding research instrumentation. Those new methods—debt financing with user charges and limited partnerships—have had some success, but also have their limitations. They should be viewed as parts of a more complex university effort to solve the instrumentation problem, rather than as complete solutions in themselves.

Debt Financing and User Charges. Universities have traditionally been wary of resorting to debt as a means of financing their activities. However, the experience of Colorado State University in using tax-exempt debt finance to purchase top-of-the-line computers, electron microscopes, and other equipment that would not have been available otherwise seems to demonstrate some possible advantages to that type of financing.[27] Debt financing may be done through the sale of such tax-exempt instruments as revenue bonds, through municipal leases, and through revolving lines of credit. It may also be accomplished directly by the interested research group, or, as in the case of Colorado State University, through an affiliated research foundation or other such organization that assists in the purchase, or actually makes it outright, and then leases the equipment to the university. Generally the equipment itself serves as the security. The debt is retired through user charges. Equipment acquired in that manner is made available to a number of users, rather than to only one, as is often the case with the grant purchase system. Sharing through user charges can result in improved equipment utilization, assuming Federal agencies include such charges as allowable costs in research grants. Unfortunately, relatively few universities have affiliated institutions with the resources to make such purchases.

One large advantage of debt financing is that it allows for more immediate acquisition of instruments. Research time and opportunities are not lost while researchers look for matching funds to cover the entire purchase price of costly instruments. In addition, the extra costs created by inflationary price increases are saved if researchers are able to buy sooner rather than later. However, the advantages of being able to start sooner on research projects may be offset by the disadvantages of having to repay the debt through user charges. Researchers may find that to generate enough user charges to repay the debt they must allocate a large amount of instrument time to other users, which may jeopardize their own research efforts. Therefore, to allow researchers to have the full benefit of instruments acquired in such a manner, it is necessary to keep the payback period short so that researchers will have full access to their instruments as soon as possible.

One final caution regarding debt financing is that universities can become locked into debt-financed projects and later be unable to commit funds to new frontier research. Administrators may feel obligated to support projects that are debt financed, rather than basing their decisions solely on research merit.

Limited Partnerships. Limited partnerships to finance high technology R&D also have been used recently to help provide funds for university research. This form of financing has become more attractive because of recent changes in the law that provide tax advantages for such arrangements.[28] Typically, under such arrangements the university and private investors join forces to provide equipment and expenditure funds for research projects; the university becomes a general partner, and the investors are limited partners. Limited partners are allowed tax deductions on costs up to the amount invested. Should the project show a profit, limited partners earn a percentage of that profit and pay capital gains taxes on that amount.

Obviously, limited partnerships are more attractive in scientific areas that promise quick, high returns on investment, for example, biotechnology. They are somewhat less suitable as vehicles through which most basic research, where payoffs can be diffuse and are not generally immediate, may be funded.

These methods of innovative financing provide some means of alleviating the problem of equipment obsolescence. They have limitations, however, and obviously represent far less than a comprehensive solution.

Intrainstitutional and Interinstitutional Cooperation. Cooperation within and among universities can also improve the availability of instruments to researchers. Too often academic departments and laboratories operate in isolation from one another and fail to coordinate equipment purchase and use. As resources become more scarce, academic units will need to develop and improve their communication, both on their own and with encouragement/pressure from university administrations. Similarly, universities will need to develop more effective means of local and regional cooperation, including sharing of expensive equipment and facilities. NSF's Regional Instrumentation Centers Program has helped encourage such sharing in some cases; additional instances need to be explored.

A related mechanism is the development of brokerage systems through which equipment could be transferred readily from one university to another. Universities engaged in pioneering research could sell nonessential equipment to other universities and colleges for training or routine research purposes and apply the proceeds toward new equipment. The Federal Government could encourage such brokerage through more flexible granting policies.

The Direct Federal Role

Regardless of the other alternatives that have been considered, the Federal Government will continue to play a direct role in mitigating the problem of instrumentation obsolescence as well as in providing incentives to stimulate corporate action. For example, funding agencies can assist by allowing more flexibility in funding procedures for research grants to make up for gaps in local funding. The current NSF requirement that equipment grants be matched on a 50-50 basis fails to account for the associated costs of equipment maintenance, housing, and servicing—costs that are increasing and not being met by local funding. Universities are, however, beginning to receive credit toward their required matching percentage from expenditures on site preparation, support facilities, operation, and maintenance. In that manner, costs to the universities are spread out over the life of an instrument.

Another mechanism that would provide flexible funding at the local level would be a carefully designed institutional grant program specifically earmarked for equipment and associated support services and based on a proportion of total direct Federal support received. Such a program would allow the diversity of needs associated with instrumentation to be met at the local level, while maintaining full Federal accountability.

The establishment of more block-funded research centers—for example, the materials research laboratories funded by the Department of Defense and the National Science Foundation—can also help to alleviate the obsolescence problem. Typically, those centers pursue general research goals, with guidance provided by the funding agency and local management. Flexible guidelines allow for the purchase of necessary but expensive, sophisticated instruments. The stability and scale of funding make possible adequate maintenance of the equipment. A recent study showed that the centers are able to provide better instrumentation for their laboratories than equivalent project-funded laboratories.[29]

Summary

The solution to the problems of instrumentation obsolescence in research universities will not come from a single answer, agency, or institutional arrangement. Rather, a concerted effort in which universities, industrial firms, and the Federal Government all actively participate should be able to ameliorate those pressing problems.

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Adequacy of U.S. Engineering Education

Abstract

Formidable problems need to be resolved if science and engineering education in the United States is to continue to contribute to the attainment of broad national goals and needs. The problems associated with the national system for educating engineers are immediate and acute. They result primarily from shortages of new engineers and computer scientists in specific specialties and sectors. Production of Ph.D.'s in engineering, in computer sciences, and in a few other critical scientific disciplines continues to decline, with potentially adverse consequences for the military, academia, and industry. Approximately 1,600 positions on U.S. engineering school faculties remain vacant, even as undergraduate engineering enrollments increase. The faculty shortages, which could lead to a decline in the overall quality of engineering education, are being exacerbated by other problems. The initiative for developing remedies for those problems rests primarily with the universities and with industry; in fact, several experiments linking universities and industry more closely have been initiated. The principal initiative for remedying problems associated with engineering education must originate primarily from the universities themselves and from private industry. However, most observers agree that the Federal Government must continue to play a role in maintaining the vitality of U.S. engineering education by focusing R&D resources on long-term research, by targeted fellowship support, and by indirect incentives to further increased university-industry cooperation.

Introduction

The diverse, decentralized set of institutions that constitutes the U.S. national system for educating and using scientific and engineering personnel has many fundamental and enduring strengths. We give our scientists and engineers high status, and they have the opportunity to make independent decisions at an earlier age than is the case elsewhere. Compared with most countries, our scientific and technological institutions are adaptable, and our market economy is (with important exceptions to be noted presently) reasonably efficient in adjusting the demand and supply of trained personnel. Our large corps of broadly educated scientists works in a system that has, in the past, provided the time, resources, and congenial environments necessary for productive work. The results have been a continuous flow of exciting findings that have revolutionized most areas of science and that can, over the decades ahead, continue to provide the technical base for new products, new processes, and new industries. Younger scientists entering the system are, as a group, as capable as their predecessors, and it is probable that investigators of outstanding talent will continue to appear.

Engineering, like science, has many strengths. Engineers today have broader and deeper backgrounds than at the end of World War II. The content of engineering education has shifted markedly in response to new scientific discoveries, changing production methods, and new materials, instruments, and products. Engineers are respected professionals who are gaining more positions of executive leadership. The number of women enrolled in U.S. engineering schools is increasing rapidly, though racial minorities are still grossly underrepresented. In contrast to the production of scientists, however, many other countries are producing greater numbers of engineers, particularly in fields in which U.S. technology is no longer predominant.

The adequacy of the Nation's scientific and engineering activities must, however, be assessed in terms of their capacity to contribute to present and future national goals rather than on their past achievements. Every review of the status of science in the United States attests to the excellence of our basic research effort, and the maintenance of that excellence continues to be an important goal. But, the Nation also needs a strong technological base that can underlie improved defense capabilities, a productive and resilient economy, and a capacity to compete in world markets. The fact that those needs are no longer being met as well as they might be suggests that the adequacy of our scientific and engineering activities, including the adequacy of our system for educating scientific and engineering personnel, requires scrutiny.

There is a broad consensus that the current and projected problems associated with the aggregate numbers, the occupational distributions, and the quality of education of U.S. scientists and engineers, as well as with the academic institutions in which many of them work, constitute a significant barrier to the full utilization of our potential scientific and technological resources.

The total pool from which future U.S. scientific talent could be drawn is not being tapped adequately. Racial minorities, with the exception of Asian Americans, continue to be woefully underrepresented in all scientific fields. Women are also underrepresented, although their increasing numbers in the life, behavioral, and social sciences is an encouraging indicator of change.

The problems facing most fields of science pose threats to the long-range vitality of our national research effort and its capacity to advance in the long run. Among the most serious is the prospective scarcity of new permanent positions on university science faculties through the 1980s and beyond, a situation that has been treated in the *Annual Science and Technology Report to the Congress, 1980*[1] and a joint National Science Foundation Department of Education study.[2] One consequence of the stagnant academic job market and the resultant perception among students that advanced study in many fields is unlikely to lead to attractive career prospects has been a steady decline over the past decade in the numbers of Ph.D's awarded in the mathematical and physical sciences. The situation could have adverse consequences beyond the universities. Industry, for example, already reports shortages of new Ph.D's in a few scientific subspecialties, and those shortages conceivably could extend to other areas as well if the decline in Ph.D. enrollments persists. A second, serious problem is the increasing obsolescence of research instrumentation in university laboratories, a problem that poses a threat to the ability of university faculties to carry out frontier research, develop new instruments that can lead to important innovations in private industry, and provide quality education for graduate students.

Perhaps the most serious, long-term threat to our national science and technology capabilities is the declining emphasis on science and mathematics in the Nation's secondary schools. That decline, in sharp contrast with the situation in other industrialized countries, is discussed in the *Annual Science and Technology Report to the Congress, 1981*[3] and elsewhere.[4]

The problems associated with sustaining and improving the adequacy of the U.S. national effort in engineering and in the computer sciences are similar. They include declining Ph.D. production, instrumentation obsolescence in universities, and underrepresentation of racial minorities. Unlike most fields of science, however, engineering faces personnel problems that are more immediate, more acute, and more of a potential barrier to increases in industrial productivity. Hence, engineering will be the primary focus of this paper.

Current and Projected Personnel Supply and Demand for Engineers

The *Annual Science and Technology Report to the Congress, 1980* noted that there were, in 1980, inadequate numbers of new graduates at all degree levels to satisfy demand in the computer sciences, most engineering specialties, and a few subspecialties in the physical and biological sciences, among them, solid state physics, optics, analytical chemistry, and toxicology.[5] A greater number of new bachelor's degrees were awarded in engineering and computer science in 1981 than in the previous year, and enrollments in U.S. engineering schools also increased. However, few observers in either academic engineering or industry believe that those increases can alleviate personnel shortages in the near future. Indeed, the perception that engineering education is in a state of near crisis may well have become more widespread during the past year.[6] Significantly, there is a growing consensus that the crisis is not simply a consequence of an aggregate balance between supply and demand for engineering personnel. Rather, quantitative inadequacies, coupled with other problems faced by U.S. engineering schools, may already be having negative effects on the quality of U.S. engineering education, effects that cannot be resolved by stop-gap measures.

There has been some question about whether—and how long—the current excess demand that lies at the heart of the crisis, or near crisis, can persist. Projections compiled by the Bureau of Labor Statistics and the National Center for Education Statistics suggest that there should be sufficient numbers of engineers at all degree levels and in all specialties by the end of the decade, though the demand for computer scientists is likely to continue to outstrip supply.[7] If the engineering job market were to "soften" in the next few years, as the projections suggest, then, it is argued, market forces would act to relieve the shortages, including severe shortages in the military and academia.

Many knowledgeable specialists question those conclusions. They point out that virtually all high-technology industries are becoming increasingly labor intensive in their use of engineers and that projection methodologies have yet to incorporate that change in utilization patterns. Moreover, it is almost certain that engineering schools cannot indefinitely increase the numbers of engineers graduated annually. Thus, present inadequacies of engineering and computer science personnel could persist for many years or even grow worse. If so, they could limit the growth rate of the Nation's high technology sector.

The current high demand for new engineers (and for Ph.D. scientists in certain critical subspecialties) could have particularly serious consequences for the quality of the Nation's defense capabilities. Because of the lucrative industrial job market, the armed services—which cannot offer competitive salaries—continue to experience difficulties both in recruiting engineers and scientists into military service and in hiring civilians for defense laboratories. The growing shortage of engineers and scientists in fields critical to defense not only weakens the in-house defense effort, but also affects essential defense contractor programs. Retention of engineers and some scientists is also a problem. For example, loss rates for military engineers increased by 20 percent during 1979 alone. Defense-related requirements are almost certain to continue to increase because of the projected growth in technologically intensive career fields, owing to the increasing complexity and sophistication of modern weapons systems and because of the permeation of new technology throughout all career areas, including administration, education, and training.

It is worth reemphasizing that aggregate supply and demand projections by themselves cannot provide precise information about whether there will be sufficient numbers of suitably qualified personnel available in specific subspecialties on the frontiers of technology—for example, in advanced energy systems and biotechnology. Even though the numbers of highly skilled people needed in such areas can be small relative to the total pool of new engineers, their availability and the ways they are utilized can be among the most important factors determining the success or failure of a high technology enterprise. Thus, in this respect, the question of adequacy becomes a matter of quality as well as quantity. It involves the capabilities and imaginative qualities of the engineers themselves, the quality of their education, and the quality of the environments in which they work.

Quality of U.S. Engineering Education

Given the likelihood that the strong demand for new engineers and computer scientists will persist, the extent to which U.S. colleges and universities can increase or even maintain the supply of graduates in those areas without compromising the quality of their education is an obvious significant question. An important related concern is the ability of U.S. universities to continue to remain in the forefront as centers of fundamental research in engineering.

General assessments of educational quality are difficult to make, in part because they are based on normative judgments. Specific personnel requirements and patterns of use differ from industry to industry, from company to company within an industry, and with time. Because many engineering schools in different parts of the country tailor their educational programs to the needs of different sectors of industry, there is a roughly parallel diversity in engineering curricula and in the ideal level of educational quality against which a given engineering school judges itself.

Despite these caveats, there are indications of a general deterioration in the quality of engineering education in the United States. A principal cause is the decreasing ability of engineering schools to recruit adequate numbers of qualified faculty members from among the declining population of engineering Ph.D's. Because the starting salaries offered by industry to bachelor's level engineers are high relative to the prevailing levels of graduate fellowship and assistantship support, just 2,489 Ph.D's in engineering were produced by U.S. universities in 1980, about 70 percent of the 3,485 produced in the peak year of 1970. The number of Ph.D's in engineering granted to foreign students with temporary visas increased by 80 percent over that 10-year period, while the number of U.S. citizens securing Ph.D's in engineering dropped by fully 50 percent.

Competition among employers for the decreasing numbers of new Ph.D's is even more intense than for those with bachelor's degrees. Faculty salaries are woefully noncompetitive with industry's. Instruments and facilities for research often lag a generation or more behind industry's, and, with research funds lagging, teaching becomes less desirable. Opportunities to work with graduate students are diminishing at the same time that undergraduate class sizes and teaching loads continue to grow.

As a result, academic careers in engineering are becoming increasingly undesirable, as evidenced by the fact that in the fall of 1980 about 1,600 engineering faculty positions in U.S. universities, or about 10 percent of the total, were vacant. Of those positions, 40 percent had been vacant for at least a year. Publicly supported colleges, which employ almost three-quarters of U.S. engineering faculty, had a somewhat higher percentage of vacancies than private institutions. Overall shortages would be far more severe if it were not for the availability of foreign faculty. Among junior engineering faculty, almost one-quarter received their bachelor's degrees outside the United States, and those with foreign bachelor's degrees constituted one-third of the engineering faculty at publicly supported institutions.

Engineering educators express widespread concern about the effects of the faculty vacancies on the quality of teaching and on the breadth of the curriculum. The proportion of full-term programs in engineering and computer science receiving certification from the Accreditation Board for Engineering and Technology had, in June 1981, fallen to 50 percent from its longstanding plateau of 70 percent; that is a striking indicator of decreasing quality. The results of a recent survey of engineering deans indicate that 80 percent have responded to the vacancy problem by increasing undergraduate teaching loads, while more than 50 percent have eliminated one or more undergraduate courses.[8]

The effects of faculty shortages on undergraduate instruction in engineering and computer science are exacerbated by the obsolescence of instructional apparatus and facilities. For example, the apparatus required to provide students with experience in the computer-assisted manufacturing methods that large U.S. companies have introduced are simply not available in most engineering schools. Thus, graduates face a serious and perhaps widening gap between their education and the requirements for creative contributions in industrial employment. Large companies with ample resources have responded by developing their own training programs. Conceivably, though not necessarily, it may be more cost-effective for industry to train new engineers to use up-to-date apparatus than to expect the universities to do so. The fact remains, however, that industry has assumed an educational function previously regarded as a province of the engineering schools. The consequences for the future of engineering education are by no means self-evident.

Declining Ph.D. enrollments, increasing faculty vacancies, obsolescence of research instrumentation, and insufficient research funds also are obvious barriers to academic research in engineering. One result is that universities are losing their capacity to conduct research in important frontier areas. For example, in computer architecture almost all the research capability resides with industry. Moreover, few universities appear able to develop research and teaching capabilities in such new areas as biotechnology.

Thus far private industry has been able to carry out much of the engineering research required for its own needs, either alone or in partnership with selected universities. However, a good deal of industrial research is focused on relatively short-term problems and in areas where industry perceives a specific need. It is highly unlikely that responsibility for conducting the bulk of the long-term engineering research needed to undergird future technologies could be assumed by industry. A further decline in academic research capabilities in engineering could ultimately have a negative effect on the education of the Ph.D's that industry needs both for research and for training much larger numbers of lesser degree holders.

The specific pressures on the instructional and research capabilities of university engineering and computer science departments, abetted by the overall strained financial condition of U.S. universities, limit the flexibility and thus the ability of those departments to respond to new needs and opportunities. The longstanding debate among engineering educators over the proper balance between science-related fundamentals and training in current industrial techniques and skills in the bachelor's degree curriculum persists. So does the question of the most appropriate content of education at the master's and Ph.D. levels. There is no consensus among experienced industrial and academic engineers and industrial managers on these questions. Most agree, however, that given the wide range in the types of engineers required by industry, academia, and government, there would be, in the best of all possible worlds, a continuing need for widely diverse and highly flexible types of engineering curricula and for a wide range of engineering schools catering to different industrial needs.

For example, leaders in high-technology industry are emphasizing the need for new types of curricula to provide engineers with better preparation in manufacturing and process design. More generally, most observers agree that it is in the long-term national interest to have a decentralized educational system with diversified curricula and goals within which individual engineering schools could do what they elect to do at a high level of excellence. That can be accomplished only if the schools have the human and financial resources required for flexibility. If the basic requirements were met—and they are not—the debate over curriculum could establish a stimulating, productive competition among the Nation's 280 engineering schools. In the absence of the basic requirements, no new approach to the curriculum is likely to be effective in providing sufficient numbers of capable students with the education they require to contribute to the realization of present and future national needs.

Potential Remedies

The intractable character of the problems facing university engineering departments is in large measure due to the fact that they have been developing over several years and are closely tied to the institutions' financial problems.

The Federal Government can and must play a role in partnership with the universities, with the State governments that support many of them, and with private industry to help reverse the deteriorating quality of U.S. engineering education. However, remedies must be consistent with the diversity and the independence from Federal control that traditionally have been sources of the unique strength of the U.S. higher education system.

The most immediate need is to attract and retain quality engineering faculties and to induce more first-rate undergraduate students to pursue advanced study leading to the Ph.D. in engineering. Measures to accomplish those ends will certainly have to include access to improved, up-to-date instruments and facilities, adequate and stable research support, and for faculty members, opportunities to work with promising, commit-ted graduate students. Most important, salaries for the 16,000 engineering faculty members in U.S. engineering schools will have to become competitive with salaries in private industry. More reasonable levels of funds for graduate fellowships and assistantships are also needed to induce those qualified to pursue full-time graduate study in engineering.

Some universities are already allowing engineering faculty salaries to be determined partially by the external personnel market and thus to rise above salaries in other departments. Not surprisingly, that policy has engendered some opposition on the grounds that rewards in academia ought to be based on excellence in research and teaching, rather than on whether there is external demand for faculty members in a particular discipline. There is also a feeling that engineering departments—unlike medical schools or colleges of business administration—ought to be regarded as integrally linked with schools of arts and sciences.

Whatever the merits or demerits of linking faculty salaries more closely with the nonacademic market, several technology-based firms have indicated their willingness to assist universities by offering financial incentives to engineering faculty and graduate students. For example, the Exxon Foundation is providing $15 million in grants to 66 engineering schools to supplement salaries for junior faculty members and for graduate student fellowships. The International Business Machines Corporation (IBM) has awarded almost 300 predoctoral and postdoctoral fellowships in mathematics, science, and engineering during the past 3 years. During the years between 1980 and 1984, IBM plans to have made 180 grants to university departments to support new research initiatives selected by the departments. The American Electronics Association has established a nonprofit subsidiary, the Electronics Education Foundation, whose goal is to provide substantial assistance, including faculty salary supplements and graduate fellowships, to universities prepared to expand their capacity to educate engineers in fields of interest to the membership of the association.

Beyond the immediate and continuing problem of arresting and reversing the quantitative decline of engineering Ph.D.'s and faculties, there is a long term need to maintain U.S. universities as centers of basic research in engineering so that they can maintain the quality of instruction at the master's and Ph.D. levels. Here, again, several companies appear to be acting on their perceptions that the long-term health of industry depends substantially on the generation of new knowledge and on the excellence of advanced education, and these results can best be obtained by the universities in partnership with industry. During the past 2 years, the Exxon Research and Engineering Company has agreed to provide more than $7 million to the Massachusetts Institute of Technology (MIT), over a 10-year period, for combustion research. Du Pont and Monsanto have completed long-term research contracts in genetics and microbiology with the Harvard University Medical School. Mallinckrodt, Inc., has agreed to supply nearly $4 million for research at Washington University on hybridoma technology.

There are also several instances in which more than one firm contributes to a specialized university research center. One of the most successful ventures is the MIT Polymer Processing Center at which firms of all sizes share in polymer research of direct interest to their businesses. A Computer Graphics Center has been established at the Rensselaer Polytechnic Institute, where almost a dozen companies study the uses of computers in manufacture and design. More recently, a Council for Chemical Research has been established with the primary purpose of increasing industrial support for university research.

Given industry's need for engineers and general agreement by universities and industry that the Federal Government should not intervene in matters of educational policy, the view is developing that closer industrial-academic engineering links are essential. A large-scale industrially financed effort that would provide long-range supplementary support for a number of university engineering schools while enabling them to become relatively free-standing professional schools could have great potential for industrial productivity. However, at present, corporate support for engineering faculties and graduate students and for long-term research at such premier institutions as MIT, Harvard, and Washington University are exceptions rather than the rule. The Federal Government can facilitate closer university-industry links by such means as tax incentives to corporations. However, few but the most enthusiastic supporters of broad industrial assistance would contend that industry can provide more than about 10 percent of the external support that U.S. engineering schools need to maintain high-quality research and instructional programs.

The Reagan Administration recognizes that it is in the national interest to provide targeted financial assistance to engineering education. The National Science Foundation, for example, has initiated a special new engineering faculty research incentive program designed to attract young high-quality Ph.D. engineers into academic careers. Likewise, the Department of Defense has increased both the number of graduate fellowships offered in engineering and science and the amount of each stipend in order to make full-time graduate study in selected fields more attractive.

In addition, the Federal Government, by supporting long-term research in engineering and science through grants and contracts, can help maintain and strengthen both research and instructional capabilities of the universities. Decisions made by Federal agencies in the ways they choose to distribute their R&D resources inevitably exert a powerful effect on the direction and quality of the Nation's entire scientific and engineering effort. The agencies can, for example, set the balance between short-range payoff and long-range investment. The Reagan Administration is making a clearer distinction than in the past between long-term fundamental research, for which support will continue to derive primarily from the Federal Government, and short-term development projects that are the appropriate province of the private sector. These policy guidelines can be interpreted as a clear signal to the agencies to focus their R&D resources on the types of long-term research that universities and centers associated with universities traditionally do best and that contribute to and strengthen their broad educational mission.

An increasingly strong partnership between industry and universities, coupled with prudent decisions on the part of Federal agencies concerning the distribution of their extramural R&D resources, could aid in arresting and reversing the deteriorating situation in U.S. engineering schools. There is little doubt, however, that universities will continue to face problems inherent in the slow growth or even the decline of overall support for science and engineering research and education. The ability of the U.S. higher education system to provide the educated personnel and new knowledge required to meet important national goals will be seriously impaired if the adverse effects of low growth rates on the Nation's R&D effort are compounded by a failure to compensate by enhancing quality. Thus, universities face the formidable problem of sustaining or elevating excellence at the same time that resources level off or actually decline. The problem is likely to be most acute for large universities that are not among the handful of premier research institutions but do, in fact, educate the overwhelming majority of engineers. Those universities will have to decide whether their goal will be to protect excellence by a more selective distribution of scarce resources or to spread their resources ever wider and thinner. In the case of publicly supported universities, State governments will have to decide whether resources will continue to be allocated on a student credit hour basis, and thus driven solely by undergraduate enrollments, or on the basis of a long-range view of the university's role in the State and the Nation.

While the burden for making those difficult decisions will continue to fall most heavily on the universities and, in the case of public universities, on State governments, the Federal Government and, most significantly, industry must recognize their stake in the excellence of the Nation's higher education system. Much of what should be done has already been started. The several experiments with new institutional forms for linking industrial firms with universities are exposing the practical problems generated by such closer linkages, and they are beginning to provide appropriate solutions.[9] The most effective Federal role should be to provide greater indirect incentives for industrial investments in academic research and education. Whether still more attention and resources will be devoted to sustaining the quality of U.S. engineering education—and

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science—depends in large measure on public perceptions of the importance, to the Nation, of maintaining both scientific and technological leadership on an international basis. It depends also on a better public understanding of the central importance of scientific and technological activities to our national needs and goals.

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Advancing U.S. National Interests Through International Cooperation in Science and Technology

Abstract

U.S. participation in cooperative international science and technology activities must rest on different premises today than it did during the era when we maintained dominance in virtually all areas of science and technology. Because financial and human resources for the conduct of science and technology are limited, opportunities for international cooperation need to be assessed with a view toward selecting those that, by extending and complementing purely domestic activities, can yield significant scientific, economic, and political benefits for the Nation. The types of intergovernmental cooperative activities best calculated to serve our interests differ considerably depending on the scientific and technological sophistication and level of economic development of the countries involved, as well as their political relationships with the United States. International cooperation in science and technology also involves entities other than governments. Private firms engage in a wide range of cooperative activities. Additionally, the relationships nurtured between U.S. universities, professional societies, and individual scientists and engineers and their foreign counterparts continue to provide significant benefits both to the institutions and individuals and to the Nation.

Introduction

Through international cooperation, countries seek to acquire benefits not possible through unilateral action. In science and technology, international cooperation provides the United States with access to concepts, data, products, and processes not otherwise available. In a fundamental sense, then, the impetus for cooperation stems from the recognition of mutual self-interest. When cooperative arrangements are functioning optimally, they serve much more than the needs of individual scientists and engineers primarily concerned with specific projects and research relationships.

International cooperation can make an essential contribution to economic development by increasing the opportunities for applying science and technology to the innovation process. It can also enhance our security by strengthening alliances and by helping other countries achieve economic progress with political stability. Additionally, it can promote the advancement of the scientific enterprise as a whole.

The phrase "international cooperation in science and technology" has been used at different times to describe different activities. It has included endeavors that are primarily political in motivation (the "space handshake" between U.S. and Soviet astronauts) as well as activities that are essentially administrative (the establishment of procedures for aircraft on international flights). Scientific cooperation has been used by governments as an exploratory probe for other joint activities with broader objectives, as was the case in the science and technology cooperation agreements between the United States and the People's Republic of China signed in 1979.[1] Withdrawal of scientific cooperation has also been used as a means of expressing displeasure with the actions of another government in a separate sphere of activity. Recent examples include the response of the U.S. Government to the Soviet invasion of Afghanistan, and that of the U.S. scientific community to the internal exile of Andrei Sakharov.

These diverse examples show how difficult it is to establish a discrete set of criteria to define international cooperation. They also show that international cooperation in science and technology can and does secure benefits valued by the U.S. Government and its citizens, as well as by the cooperating entities—other governments, intergovernmental agencies, private corporations, and private sector organizations. The basic rationale for maintaining international scientific and technological cooperation is that it is among the most effective and efficient ways to gain certain benefits, whether scientific, political, economic, or a mixture.

The Changing Context of Cooperation

Although instances of international cooperation in science and technology have occurred throughout history, such cooperation has grown in importance since the end of World War II, as the scale and pace of scientific research and technological development have increased and as the benefits of cooperation have become more generally acknowledged. Cooperative study of natural phenomena that are global in nature has led, for example, to improved understanding of the lithosphere, the atmosphere, and the magnetosphere. Among the results are an increased ability to predict the location of hydrocarbon fuel deposits, more accurate weather forecasting, and greatly improved electronic communication. The linking of land masses through high speed air transportation rests on a more technical, less scientific basis of cooperation, including agreement on the use of the radio frequency spectrum, joint management of communications satellites, and common standards for traffic control. The list of such efforts is lengthy, and the United States has been an active participant in many of them.

At the end of World War II, the United States was widely regarded as the world leader in virtually all fields of science and technology—a status that rested in part on the wartime destruction suffered by most other advanced industrial nations. More recently, the U.S. position has begun to erode, and it has become necessary to recognize that this country can no longer expect to be preeminent in all fields. The United States assisted in the reconstruction of Japan and Western Europe, including the restoration of their scientific structures and technological capabilities. As those nations regained their intellectual and productive capabilities, they began to devote larger shares of their gross national products to nonmilitary research and development. Especially in Japan and West Germany, that allocation of resources has contributed substantially to the competitiveness of their products in international trade.

Yet the resurgence of the economies of those industrial nations has by no means swept the United States from its leadership position in all areas of science and technology. The award of Nobel prizes in many fields, the high level of U.S. scientific productivity (as measured, for example, by publications), and continuing U.S. technological resourcefulness (represented by numbers of patents and licenses) all evidence the continued high quality and fundamental strength of U.S. science and technology.

Nonetheless, it is apparent that U.S. participation in international cooperation in science and technology rests on quite different premises today than it did a short time ago. Other industrial nations have gained strength and effectiveness. Some developing nations have begun to challenge the leaders in particular fields. The leadership of one nation in all fields of science and technology is no longer possible. Rather, the Federal Government must scan and evaluate foreign science and technology on a systematic basis to seek opportunities for international cooperation. Such cooperation serves U.S. interests by supplementing U.S. capabilities, by increasing the knowledge base, or by enhancing awareness of discoveries with commercial or security implications. Further, the Government must have the information and intelligence resources to assist private firms in maintaining their competitiveness with foreign firms, and it must have the knowledge and the organizational flexibility to become a partner in new cooperative arrangements linking participants from the public and the private sectors.

A Typology of Cooperative Activities

Opportunities for cooperation should be judged by their potential for serving the national interest as well as the interests of the parties directly involved. A rough typology divides cooperative activities according to the character of the principal entities involved—governments, the private sector, or a combination. Recent experiences in each type of cooperation are described below.

Intergovernmental Cooperation

Intergovernmental scientific and technological cooperation can be further subdivided according to the nature of the countries involved and their relationships to one another. There are five principal (occasionally overlapping) subcategories:

- cooperation in support of military/political alliances;
- cooperation with industrial nations;
- cooperation with Communist countries;
- cooperation with developing countries, and
- cooperation through multilateral institutions.

Cooperation in Support of Military/Political Alliances

Scientific and technological cooperation among nations that have similar cultures and values and are aligned politically and militarily is the easiest to conduct and generally promises useful results. Opportunities for cooperation with allies should be evaluated according to both direct scientific or technological benefits and such ancillary objectives as the mutual (or, in some cases, one-sided) strengthening of economies and contributions to military capabilities.

Scientific and technological cooperation with the North Atlantic Treaty Organization (NATO) is, of course, a key example. Scientific cooperation within NATO was initiated in the early 1960s, largely in response to Sputnik, and was seen as a way to broaden the scope of involvement in the mutual security of the Western nations. Today, cooperation within NATO provides a mechanism for addressing our allies' concerns about the U.S. role in the strategic relationship and aids in the sharing of scientific knowledge. A program of scientific seminars, fellowships, joint projects, and institutes was developed under the NATO Science Committee. Such cooperation has been modest in size, pragmatic in orientation, and generally beneficial to the national science establishments and to the individual participants.[2] The prospect of expansion of NATO membership and activities on the southern flank (Spain, Portugal, and Greece) raises the possibility of NATO collaboration in the application of science and technology to economic development.

In the 1970s, through the initiative of the United States, which was seeking to broaden existing alliance relationships, the Committee on the Challenges to Modern Society (CCMS) was organized within NATO to examine a range of common concerns having a scientific or technical component, for example, automobile safety and air pollution. Although CCMS laid the groundwork for an expansion of scientific and technological cooperation within NATO, little action was taken to effect its recommendations. It may be opportune now to assess the usefulness of those recommendations or perhaps to mount a new effort aimed at developing scientific and technological linkages within that key security relationship, NATO.

Cooperation in Support of Economic Relationships with Other Industrial Nations

Observers of international relations have remarked on the movement toward greater economic and technological interdependence among the advanced industrial nations of North America, Western Europe, and the Western Pacific.[3] Scientific and technological cooperation among the Western industrial countries can provide a means for conserving resources while pursuing common scientific objectives.

The most experienced vehicle of scientific and technological cooperation among those nations is the Organization for Economic Cooperation and Development (OECD). Although much of OECD's work is concentrated at the policy level, joint research projects, some involving the United States, also contribute to the goals of the organization and its members. Research in energy, biotechnology, and satellite communications may be future candidates for cooperation because those areas have a high priority on the national agendas of many OECD nations.

OECD sponsorship of collaborative projects (for example, Eurochemic, the Dragon reactor) has tended to remain Europe-centered. However, there has been considerable nuclear research exchange between the United States and European countries on such issues as radiation-induced metal fatigue. In addition, French and German commitments to developing a breeder reactor may offer an opening for expanded cooperation. Continued and enlarged cooperation in breeder reactor development not only would assist our allies but also would help the United States keep abreast of a rapidly changing technology. OECD could provide the proper institutional setting for cooperative breeder research and development and could (along with its satellite organization, the International Energy Agency) provide a proper setting for designing a more productive approach to such complex issues as radiation health and safety, waste disposal, and plutonium reprocessing.[4,5]

U.S. cooperation outside Western Europe is conducted through a varied set of bilateral relationships. With Israel, for example, there are three endowed binational foundations for support of R&D projects of interest to investigators in both nations. The cooperative program with Japan is financially the largest, and it comes closest to parity in the contributions of the two governments and in the joint mechanisms used for the approval of proposals. These two examples suggest that where the will to cooperate exists, it is possible to design instruments unique to the relationships and mutual interests of the nations involved.

In the case of Canada, many areas of potential cooperation are presented by our extensive common border, similar cultures, and close relationship in security affairs. Weather modification and acid rain are typical of many areas of parallel interest in which scientific and technological efforts could be coordinated and, if properly handled, could contribute to a narrowing of policy differences between the two countries.

A special opportunity—and problem—is posed by our southern neighbor. The acceleration of Mexico's growth rate, based on the exploitation of its oil resources, suggests the possibility of enhanced scientific and technological relationships. While the balance of immediate benefits would tend to favor Mexico, except in such limited areas as arid zone agriculture, recognition of long-term mutual interest may facilitate joint projects of broader concern. Likely candidates for cooperation include ocean fisheries, transborder industrial pollution, water resources, and earthquake prediction. Clearly, a combination of strategic and economic factors makes seeking to improve the level and substance of scientific and technological cooperation with Mexico quite attractive.

Cooperation with Communist Countries

Scientific cooperation with Communist countries can serve as a window for the U.S. on scientific developments in those nations, can maintain communication linkages with important scientific communities, and can gain information of value to U.S. scientists and policymakers. At times it can serve to lay the groundwork for improved political relations and for communication in nonscientific spheres. Conceivably, it can also lead to mutual scientific and technical benefits and even to economic advantages.

At present, relationships with Communist countries are at a sensitive juncture. The response of the Federal Government, private organizations, and individual scientists to Sakharov's exile and to the invasion of Afghanistan has resulted in substantial reductions in exchange and communication with the Soviet Union, although there continue to be some exchanges at the working level. The reduction has occurred in the context of broader changes in the political climate between the United States and the Soviet Union. It is therefore time to reassess the mode of scientific and technological interaction between the two countries. As part of that reassessment, a number of important questions deserve wide discussion in government and the scientific community: Should the government continue to play a central funding role? Are the existing institutional structures of exchange providing satisfactory access to Soviet research and development activity? Is reciprocity—so essential to the character of the relationship—adequately respected on both sides?

There are some areas in which U.S.-Soviet cooperation may be of substantial mutual benefit. Continued—if not expanded—cooperation in Antarctic research may be one opportunity, especially in light of recent concerns about exploitation of marine and mineral resources. A cooperative approach to various safeguards in reprocessing spent nuclear fuel is becoming imperative as both the United States and the Soviet Union enter more actively into supplying services for other nations.[6]

While formal mechanisms surely have their place, the major facilitating role of informal links among scientists has not been generally recognized. Many observers believe that scientific exchange and communication have served as a form of "tension management" between the United States and the Soviet Union. They have been one means of expressing continuity of mutual interests and are a mechanism the two nations employ for dealing nonthreateningly with each other. Occasionally, scientific relationships become the vehicle for communicating something larger. Such were the contributions of scientists connected with the Pugwash Conferences on Science and World Affairs and of the informal contacts leading eventually to a limited test-ban treaty in 1963.[7] However, the Soviet scientists who participate in such exchanges often do not have access to political levels of decisionmaking comparable to those of their American counterparts. That, of course, can limit the value those exchanges have for U.S. scientists. The National Academy of Sciences Committee on Arms Control and International Security quite recently has begun to cultivate personal contacts in the Soviet arms control community. So far the effort has been privately supported, although even informal official approval no doubt would facilitate their task of quiet diplomacy, which offers the hope of laying a solid groundwork for future intergovernmental negotiations.

Scientific and technological cooperation has made significant contributions to the stabilization and improvement of relations with the Warsaw Pact countries. Such cooperation is not merely an inexpensive substitute for candid interaction on major differences. Rather, it is a means of maintaining the personal and professional relationships that underlie and often facilitate more formal levels of interaction. It is also a mechanism for maintaining access to a vigorous and productive scientific and technological establishment. Bilateral scientific exchange programs with the nations of Eastern Europe are distinct from programmatic relations with the Soviet Union. The Eastern European programs are not large, but they do represent an important conviction regarding the independence of action those governments enjoy vis-a-vis the Soviet Union.

Cooperation with Developing Countries

Cooperative efforts with developing countries can serve a variety of U.S. interests. Like other programs that support economic and political development, scientific and technological cooperation efforts can contribute to such U.S. objectives as the maintenance of political and economic stability in volatile regions, the strengthening of regimes friendly to the United States, the cultivation of political support for the United States, and the enhancement of markets for U.S. industry. In addition, certain types of cooperation can strengthen the scientific infrastructure in developing countries and enhance the capabilities of scientists in those countries to work as partners with U.S. scientists. In turn, the U.S. scientific enterprise can benefit from access to unique physical, biological, or cultural resources (for example, archaeological sites) in developing countries.

Assistance to and cooperation with developing countries is important because of the leverage value of science and technology when applied to development needs. More efficient use of limited resources can be achieved where there are established mutual interests: agricultural research, the identification and utilization of natural resources, alternative energy sources, and the preservation of cultural resources are examples. All proposals for cooperation should be subjected to the essential tests of common interest and legitimate reciprocity.

Scientific and technological cooperation with developing countries has two aspects. One, involving the newly industrializing countries, is comparable to cooperation with industrial nations, whether military allies or not. The other is not cooperation in the same sense, but assistance aimed at building up the capacity to cooperate. Such assistance is a relatively inexpensive strategy with considerable potential for leveraging the development process. Used carefully, it can greatly improve the productivity of human resources, introduce modern technology in ways that shortcut the normal incremental process of technical change, enhance the political stability of developing countries, and create new sources of industrial raw materials and new markets for U.S. products.

Furthermore, there are benefits to U.S. science and technology from cooperation with developing countries. Research on human fertility and family planning has benefited from data generated in South Korea, Taiwan, and India. Plant genetics has shifted its focus and methodology, partly as a result of experiments leading to new strains of rice, wheat, maize, and potatoes introduced in developing countries. Wildlife conservation depends upon scientific and administrative initiatives by those governments of Latin America, Africa, and Asia that control important yet dwindling populations and breeding grounds.

Some developing countries are virtually certain to become more significant contributors to world science and technology. They will no doubt include Brazil, the People's Republic of China, India, and Mexico. All are moving rapidly along a path of self-sustained economic and social development. Intergovernmental relations, trade, and the involvement of private firms and organizations in those countries are all likely to increase. As that occurs, questions will be raised about the character of cooperation with societies in which significant segments will increasingly resemble industrial society rather than the developing model, but which will still have large backward sectors. Of particular importance will be issues regarding the appropriate roles to be played by the public and the private sectors.

The People's Republic of China is a special case, because the technical communities in that nation and the United States are enjoying a "honeymoon" after a long hiatus in relations. There has been considerable movement in China recently toward a more pragmatic and less ideological approach to the United States. Among the developing nations that will have the resources to play a major role in world affairs in the coming years, China ranks high. It is therefore essential for U.S. policy planning to develop both formal and informal relationships with the individuals who will guide China's scientific and technological modernization.

There are similar reasons for U.S. interest in cooperation with such other large and populous developing countries as India, Indonesia, and Egypt. Each possesses the combination of strategic location, large human and natural resources, and awareness of the potential that science and technology can have for facilitating development. In such countries, the United States might explore the feasibility of combining the capabilities of the government with those of the private sector to increase the contribution of science and technology to development.

A number of nations, collectively known as Agency for International Development (AID) "graduates" because they no longer meet the per capita income criteria for U.S. development assistance, could be more consistently engaged in scientific and technological cooperation yielding mutual benefits. Steps to strengthen AID have already been taken through internal reorganization and the approval of a research program managed by the National Academy of Sciences' Board on Science and Technology for International Development (BOSTID). The BOSTID program is unique in U.S. experience because of the extent to which it engages representatives of developing countries in the selection and execution of research projects.

An effective approach to those nations that have evolved beyond the need for development assistance is suggested by the International Development Cooperation Administration's Trade and Development Program (TDP). TDP authorizes the use of U.S. Government resources for development, but with funding provided by the developing country. Small dollar commitments are available for studying feasibility and for other preparatory activities leading to projects in which the private sector could have a major role.

Throughout the developing world, there is and will continue to be a strong demand for the application of science and technology to the goal of modernization, regardless of whether such applications fall under the rubric of assistance or cooperation. The United States has limited resources and will have to respond to its own priorities in deploying them effectively. Three basic principles might provide some guidance in deciding which requests for cooperation and assistance are most important to meet. First, to be effective, both cooperation and assistance should have continuity. Second, if both the United States and a developing country can articulate their scientific and technological interests candidly, the identification of points of convergence where sustainable cooperative enterprise can be focused will not be difficult. Third, assistance programs should provide means for the developing country to outgrow U.S. tutelage, so that the activity becomes self-sustaining and can be carried on largely with indigenous personnel.

Cooperation through Multilateral Institutions

In recent years, a number of issues with considerable scientific and technological components have surfaced in the deliberations or programs of the United Nations. Although some U.N. agencies have become politicized forums for confrontations over economic and political issues, certain scientific and technological activities are performed effectively by such agencies in a manner supportive of U.S. policies and interests. For example, positive results are emerging from the global monitoring and program development initiatives of the U.N. Environment Program (UNEP). UNEP has been in existence for less than a decade, but it has been responsible for important programs now beginning to bear fruit: the Global Environmental Monitoring System, the International Register of Potentially Toxic Chemicals, and the Regional Seas Program, including a Caribbean Action Plan for the development of tourism and economic growth.

Such long-established agencies as the International Atomic Energy Agency (IAEA) and the World Meteorological Organization (WMO) also perform functions that would be difficult to carry out in any other way. The IAEA mission is of particular interest to the United States as uranium-fueled generating and research installations become more numerous and the dangers of nuclear weapons proliferation become more pressing. The U.N. Development Program (UNDP) and WMO stimulate the growth of scientific and technological capacities in developing countries and coordinate national programs in the industrial countries. Because of the relative efficiency of cooperation as compared with independent action, those activities of the United Nations are likely to be consistent with U.S. priorities, even at a time when funding for multilateral activities is undergoing severe scrutiny.

Among the most notable achievements of the United Nations and its organizations have been such scientific and technological accomplishments as the eradication of smallpox through the efforts of the World Health Organization (WHO). In essence, that was the result of a massive cooperative enterprise in which WHO acted as the global planner and manager.

However, there are increasing needs for the performance of technical tasks on a global basis by institutions that are not now an integral part of the world organization.[8] Among intergovernmental organizations not associated with the United Nations, the International Marine Consultative Organization (IMCO), the International Bank for Reconstruction and Development (a part of the World Bank), and the International Telecommunications Satellite Consortium (INTELSAT) play roles of particular benefit to U.S. interests. Through competent technical staffs and clearly defined technical missions, they have been able to maintain effective programs even in periods of financial restraint.

As a final note on cooperation through multilateral institutions, the prospect of broadly international, even worldwide, collaboration in the pursuit of "big science" deserves mention. Until now, the United States has managed to build and operate its own large instruments for research in high-energy physics and has managed to bear the costs of such expensive areas of space science as planetary exploration. As the next generation of efforts in those fields begins to take shape, it will be necessary to confront the reality that the costs are likely to be too high for any single nation—even the United States—to bear alone. The nations of Western Europe have already faced that situation and pooled their efforts in a number of successful enterprises, including the European Organization for Nuclear Research (CERN) and the European Space Agency (ESA). American and, possibly, Japanese, Soviet, and other participation in large-scale efforts of that type may be a financial necessity for all concerned if frontier areas of basic science are to be explored. New modes of cooperation will require careful study during coming years.

Cooperation Among Private Firms

Scientific and technological relationships that cross national borders may, and often do, involve entities other than governments. Private firms maintain a wide range of activities and relationships that are international in nature—some cooperative, others competitive. Defining exactly what constitutes international scientific and technological cooperation among private firms is not easy. A great deal may occur that is neither visible to government policymakers nor particularly susceptible to conscious government intervention. Little has been written to guide systematic thought. A careful analysis of the appropriate roles the private sector can play in international scientific and technological cooperation should be conducted to determine the extent to which such cooperation is in the national interest and should be expanded.

Private firms can make a significant contribution to the development process and to U.S. policy objectives through cooperation with firms in developing countries. There is no single model for such cooperation, though a method that has worked in the past is for the U.S. firms to provide cooperating firms in developing countries with experienced personnel to oversee production, manage facilities, and market products. Beyond that type of assistance—which would be continued and expanded—a larger and better coordinated effort to bring new technologies into developing countries through the private sector might be mutually beneficial. The Trade and Development Program, mentioned above, is a promising start.

Private firms have cooperated successfully across national borders in such fields as commercial utilization of space, aircraft engines and airframes, computer software, and automotive product development. Those areas will continue to be attractive because costs are high, risks are large, and there is a global market for a relatively homogeneous product or service. In lieu of direct assistance, the most significant government contribution may be the reduction or elimination of regulations and other controls that inhibit the development of cooperation that serves U.S. interests. The United States has had a long and recently renewed interest in controlling the export of high technology goods and services to Communist nations. Although the current approach is to extend that control to classes of technology, rather than individual products,[9] the problems remain formidable. Some observers believe that the United States stands to lose more in the long run than it might gain by restricting the export of technology.[10]

A large and growing area of corporate cooperation lies in cross-licensing and technology-sharing agreements. Those mechanisms provide quick access to new technology without investments in costly and open-ended research. They do, however, have the drawback of contractual limits on markets where the product may be sold or the service offered, and they require that the supplying firm have assured access to improvements developed by the receiving firm.

The growth of the multinational corporation may be the most important response of the private sector to new opportunities for cooperation across national boundaries. The essence of the multinational's capability is to maximize advantage by siting operations where cost factors are most favorable. New studies of cooperation among multinationals could examine on a sectoral basis the effects of international cooperation on national firms and markets.

Intersectoral Cooperation

International cooperation in science has long been pursued by scientists—with or without the support of their governments—in a nonpolitical and mutually beneficial fashion. Large-scale enterprises began with the International Polar Years in the late 19th and early 20th centuries. Such cooperation has been greatly extended in recent years through such investigations as the International Geophysical Year, the International Decade of Ocean Exploration, and the International Biological Program. Large-scale projects depend ultimately upon links among working scientists in both the private and the public sectors. Those links are maintained through disciplinary organizations at the national level and the International Council of Scientific Unions (ICSU) at the international level. ICSU has organized cross-cutting teams to examine scientific questions relating to the environment, the Antarctic, and the developing countries. In recent years, engineering societies have developed a similar global organization, the International Council of Engineering Societies (ICES). During 1981, following a Global Seminar organized in New Delhi, India, by the Indian Science Congress Association, the Indian National Science Academy, and the American Association for the Advancement of Science (AAAS), a continuing committee was formed linking scientific and engineering societies worldwide for the purpose of contributing to development.

Fragile human networks, established through meetings and cooperative projects, are among the principle means of circulating, evaluating, and stimulating new ideas. Travel and communication are obviously essential to the health of those activities. The decline of funding for international activities has been one explanation for the decreasing involvement of U.S. scientists in international organizations and meetings. Finding ways to ensure that such activities are maintained is an important challenge to the scientific community.

A new type of institution, the prototype of which is the International Rice Research Institute (IRRI) at Los Banos, Philippines, has developed in the last two decades. The International Corn and Maize Institute (CIMYT) in Mexico and the International Center for Insect Physiology and Ecology (ICIPE) in Kenya are examples. Each is privately incorporated in the country where its work is carried out, but its board of directors is international. The Consultative Group for International Agricultural Research (CGIAR), a supporting structure made up of national governments and the World Bank, plans and coordinates funding for IRRI, CIMYT, and a number of similar centers. These new types of institutions have been among the most effective instruments of fundamental U.S. development and assistance policies in recent years.[11]

Many universities and colleges have satisfactory, long term experience with international cooperation in science and technology. The agricultural programs of Cornell University and the University of Minnesota are examples. Extending those relationships and developing new ones in fields critical to the development process would be in the interest of both the United States and the developing countries. Though this may lead to the export of jobs, recent data show that U.S. trade with developing countries is the most rapidly increasing portion of the Nation's foreign trade, suggesting that offsetting benefits do exist.[12]

The high proportion of foreign nationals currently enrolled in graduate science and engineering programs in the United States is a cause of concern to developing nations, who fear a "brain drain," and to U.S. observers concerned about the costs to U.S. institutions and to State governments (in the case of some state universities). The interest of U.S. institutions was strongly articulated following the U.S. agreements with the People's Republic of China in 1979.[13] Given adequate preparation and financial support, training programs in the United States and abroad for developing-country personnel in such fields as civil engineering and agricultural science could strengthen our own institutions, help developing countries gain their most needed resource (trained scientists and engineers), and provide the basis for future professional and commercial relationships.

Conclusion

The opportunities for international cooperation in science and technology are numerous. Different modes of cooperation offer different costs and benefits, and their contributions to the fundamental U.S. interests of economic growth and national security need to be assessed. Since American preeminence is no longer possible in all areas of science and technology, careful attention needs to be paid to ways in which international cooperation can complement domestic R&D efforts, conserve scarce financial resources, help U.S. industry maintain or improve its international competitive position, and contribute to U.S. political and security objectives.

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